THE APPLICATION OF GEOPHYSICS IN LOCATING BURIED HAZARDOUS WASTES AND IN MAPPING GROUNDWATER CONTAMINANT PLUMES

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[1] GRIDEPTH® is a registered trademark of Simon Robertson P.L.C

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1.0 INTRODUCTION

The purpose of this report is to outline the applications of the primary geophysical methods used in environmental problems and provide practical examples through case histories where the methods have been applied. The descriptions of the methods used are intended as brief outlines to provide basic understanding of the methods only. If greater understanding of the physical principles behind the methods is desired, the references given at the end of the report or any geophysical text should be consulted.

The use of geophysics in locating buried hazardous wastes and in delineating contaminant plumes from buried wastes or spills is now common practice. Geophysical instruments which have little or no contact with the ground, record data at selected intervals along grid lines enabling large areas to be covered without causing any negative impact on the land. From the interpretation of this data, conceptual cause and effect relationships can be developed, features of interest or concern can be delineated and, most importantly, efforts toward extraction, remediation and/or monitoring can be focussed and localized. For many environmental problems such as location of buried tanks and drums, outlining areas of illegal or closed waste sites and delineating contamination plumes from highly conductive sources, geophysics has proved to be an efficient and cost effective method. With the high cost of clean-up of contaminated sites combined with the legal responsibilities of owning such properties, developers of new properties want some assurance that properties which they may want to acquire are not contaminated. In many cases, geophysics can provide valuable information outlining areas that require clean-up and, when the work has been completed, assurance that clean-up has occurred.

It is important that the geophysical method and instrumentation chosen be the most effective for the particular problem at hand. In many cases more than one method is applicable. The geology, depth of investigation, type of anomalies expected (ie. ferrous, non-ferrous, conductive, non-conductive) may eliminate some choices or make some choices more effective than others. Some of the more traditional geophysical methods such as seismic and conventional resistivity, have an important role where mapping geology is important; these methods, however, are more time consuming and labour intensive. The methods which will be discussed here can all be conducted efficiently with two person crews and in some cases by a single operator. All methods have advantages and disadvantages which will be outlined under geophysical applications.

The surveys described in this report are all conducted in a similar manner where data are recorded along grid lines at specified intervals. The line spacings and recording intervals are chosen to provide sufficient data to delineate the target. The main factors to be taken into account when choosing the line spacing and recording intervals are the horizontal resolution of the instrument used in the survey, the instrument noise level caused by culture sources and the size, shape and depth of the target.

2.0 GEOPHYSICAL METHODS

2.1 MAGNETIC

The earth can be considered a large bar magnet with both a north and south magnetic pole (dipole). As in a bar magnet, the density of the lines of flux surrounding the earth is a function of the earth's total magnetic field intensity. The unit of measurement for magnetic intensity is the nano Tesla (nT) or gamma. The intensity of the earth's total magnetic field is strongest at the magnetic poles (60,000 nT) where the total magnetic field is vertical, and weakest at the earth's magnetic equator (30,000 nT) where the total magnetic field is horizontal. North or south of the magnetic equator, the total magnetic field can be broken into vertical and horizontal components. The intensity of the earth's magnetic field at any point on the earth's surface is known and varies slowly with time. Since the intensity of the earth's magnetic field is known for a given location, this background value can the be compared with anomalous values recorded due to the presence of ferrous metals.

The instruments used to measure the earth's magnetic field are called magnetometers. There are various types of magnetometers such as fluxgate, proton and Overhauser proton. Some measure only the vertical magnetic field while others measure the total magnetic field. Magnetometers with two sensors spaced at some distance apart are called gradiometers. With these instruments the gradient field can be calculated by subtracting the difference between the total or vertical field values recorded by the two sensors, and by dividing that value by the distance between the sensors.

In environmental investigations, the primary objective of magnetic surveys is to locate buried ferrous metallic objects below the earth's surface. Ferrous metallic objects create anomalous values in the earth's total magnetic field which are measured and compared to the background magnetic field for the area. These anomalous magnetic fields are due to two types of magnetism called induced and permanent magnetism. Induced magnetism is the effect the earth's field has on the ferrous metal which causes the metal to become magnetized. The north and south poles of the

metal due to the induced magnetism will be in alignment with the earth's poles. Permanent magnetism is dependent primarily on the metallurgical properties of the metal and the alignment of the permanent field could be in any direction. The vector sum of the induced and permanent magnetic fields within the same metallic object may add or subtract from each other. The maximum magnetic intensity caused by a ferrous metallic object is when the object is orientated so that the permanent magnetic field is aligned with the induced field.

The general formula for estimating the maximum amplitude of any anomaly in cgs units is:

$$T = \frac{M\,(10^5)}{r^n}$$

where

	T =	anomaly in nano Tesla
	M =	magnetic moment
	r =	is the distance from the sensor to the centre of source.
	n =	is the fall-off rate (n=3 for a dipole, and n=2 for a monopole).

The major factors effecting the detectability of an object with a magnetometer are as follows:

(a) the depth of burial.
(b) the amount of ferromagnetic material contained by the object (magnetic moment).
(c) the orientation and shape of the object.
(d) the magnetic noise surrounding the object.

For dipole anomalies; such as tanks and drums, the total field response varies inversely as the cubed root of the depth below the sensor. This means that if the distance between the magnetometer and the object was doubled, the magnetic response would be reduced by a factor of eight. For this reason the practical depth for locating a single buried 45 gallon drum is between 2 and 3 metres. The second factor in locating buried metallic objects is the magnetic moment of the object. Breiner[4] describes the magnetic moment of an object as "the degree of magnetism of the material times the volume of the material". He also states that "for typical man-

made iron or steel objects, the magnetic moment, M, is between 10^5 and 10^6 cgs units per ton (either 1000 kg or 2000 lbs)". The third factor is the orientation and shape of the object. The orientation of the object is important since the total magnetic response is the vector sum of the induced and permanent magnetic fields which may add to or subtract from each other as described earlier. The shape of the object is also a factor in the magnetic intensity. For example, a crushed drum does not give as large a response as a normal shaped drum even though the amount of metal is the same. Finally, the magnetic environment where the object is buried has a large bearing on whether it can be detected or not. For example it would not be possible to locate an object with a magnetic response of 50 nT in an environment where it was buried with objects that had a magnetic response of 100 nT. Cultural effects like buried pipe lines, electrical and telephone cables, buildings, ferrous metallic debris and reinforcing steel in concrete are a few sources of magnetic noise which may create problems when carrying out magnetometer surveys.

2.2 ELECTROMAGNETIC (Frequency Domain)

There are two types of electromagnetic measurements referred to as frequency domain and time domain. In general terms, frequency domain instruments measure the relative strength of a continuous secondary magnetic field while the time domain instruments measure the decay of a pulsed secondary magnetic field. The electromagnetic instruments used in this publication are all frequency domain instruments with the exception of the EM-61 Metal Detector which was used as part of the investigation for locating buried drums in Elmira, Section 4.12.

An electromagnetic survey is a geophysical method for mapping the terrain conductivity of the earth by induction. The most significant natural variations in terrain conductivity of the earth are porosity, conductivity of soil moisture, degree of saturation and the presence of clay or bedrock. The general principle behind how the terrain conductivity is measured with electromagnetic instruments is described by McNeill (1982) as follows: "A small transmitter coil is situated on or close to the earth as illustrated in Figure 1. An alternating voltage, typically at an audio frequency, is applied to the terminals of this coil, causing a current to flow. This current generates an alternating magnetic field, (Primary Magnetic Field) which through Faraday's Law, causes electrical current to be induced in the earth (no such current is induced in the air, which is effectively infinitely resistive). The induced current in the earth generates a secondary magnetic field. Both the primary and the secondary fields are detected by a receiver coil located near the transmitter coil, as shown in Figure 1, and in principle, measurement of the ratio of the secondary to the primary magnetic field strength can be used to determine the electrical resistivity of

the earth". Under certain constraints, defined as low induction numbers, the ratio of the secondary field to the primary magnetic field is linearly proportional to the terrain conductivity of the earth. Under these conditions, the receiver records the value of terrain conductivity directly.

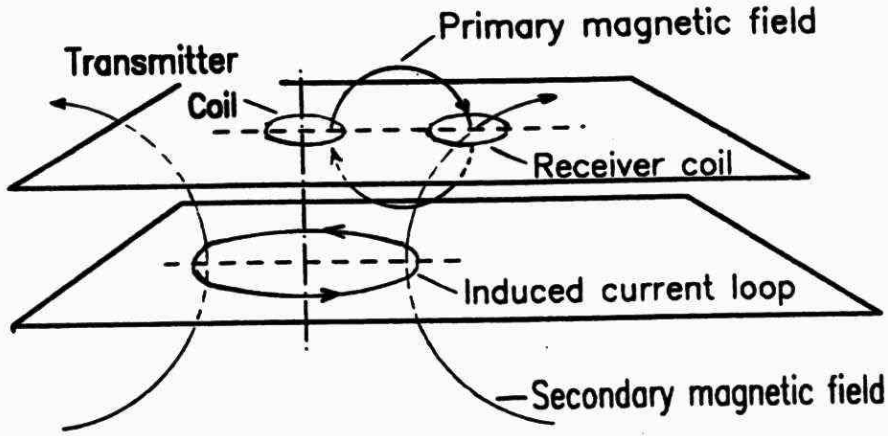


Figure 1. Inductive electromagnetic fields (From McNeill, 1982).

Electromagnetic methods have been used for many years in the mining industry for locating ore bodies. It was not until 1975 that the first electromagnetic instrument was designed for shallow terrain conductivity mapping for use in helping resolve environmental problems. The two instruments most often used are the EM-31 and the EM-34 which display values of terrain conductivity directly. The units of measurement are milliSiemens per metre (mS/m) or millimhos/metre (mmhos/m). The effective depth of penetration for these instruments is determined by mode of operation, either vertical or horizontal dipole mode, and the distance between the transmitter and receiver coils. In the case of the EM-31 the coil spacing is fixed at 3.7 metres; the effective depth of penetration is 6 metres in the vertical dipole mode and 3 metres in the horizontal dipole mode. With the EM-34, the intercoil spacing can be adjusted to 10, 20, and 40 metres; the depth of penetration is 0.75 or 1.5 of the coil separation when the instrument is operated in the horizontal or vertical dipole modes respectively.

In the EM-31, two components of the induced magnetic field are measured. The quadrature-phase component is the normal terrain conductivity measurement; the inphase component, which is very sensitive to large metallic objects, can be used in search of buried tanks, drums and other metallic targets.

2.3 VLF RESISTIVITY

The VLF (Very Low Frequency) Resistivity method uses carrier waves from military transmitters as a signal source. The transmitters presently operating in North America are located in Cutler, Maine and Jim Creek in Washington State. The transmitter frequencies for the above stations are 24.0 kHz and 24.8 kHz respectively. There was also a transmitter in Annapolis, Maryland operating at a frequency of 21.4 kHz until 1997. The principle governing the operation of the VLF Resistivity method as described by Greenhouse and Gudjurgis[5] is as follows: "At a large distance from a VLF transmitter, the radiated field is a plane wave that consists of a horizontal magnetic field perpendicular to the direction of propagation, a horizontal electric field component in the direction of propagation, and a vertical electric field component." When conductive bodies within the earth are encountered, the current flow channels through the conductive body and creates a localized increase in the horizontal magnetic field strength. The VLF receiver measures the amplitudes of the horizontal electric and magnetic field components. The ratio of these field components is used to calculate the apparent resistivity of the earth. The phase angle is also measured between the horizontal electrical field and the horizontal magnetic field. When the phase angle is 45 degrees, the earth is homogeneous down to the depth of investigation and the apparent resistivity will be the true resistivity. In a layered earth with more than one resistivity a phase angle of less than 45 degrees indicates the resistivity of the earth is increasing with depth, and when the phase angle is greater than 45 degrees the resistivity of the earth is decreasing with depth. Knowing whether the earth is homogeneous or whether the earth's resistivity is increasing or decreasing down to the depth of penetration of the instrument is useful in both the interpretation of the geology and possible effects due to contamination.

The depth of penetration of this method is a function of the overburden resistivity and the operating frequency and is referred to as the skin depth. The approximate depth of exploration is roughly 2/3 of the skin depth (McNeill, 1990).

$$\text{skin depth (m)} = 500\sqrt{(p/f)}$$

where p = resistivity (ohm-m)
f = frequency (Hz)

2.4 GROUND PENETRATING RADAR

Ground penetrating radar is an electromagnetic method which operates at very high frequencies in the range of 10 to 500 MHz for environmental studies[5] compared to VLF operating frequencies of 15 to 30 kHz and EM conductivity meters with operating frequencies of 0.4, 1.6, 6.4 and 9.8 kHz. The size and depth of the feature that can be detected by GPR is dependent on both the operation frequency and the geology. Davis and Annan[8], 1992, indicate that GPR can detect fractures a few millimetres thick at a distance of a few metres using a frequency range of 500 to 1000 MHz, and can penetrate in excess of 50 metres in geological formations with low conductivity (less than 1 mS/m) such as sand, gravels, rock and fresh water at a frequency range of 25 to 50 MHz. The lowest penetration is in fine grained material such as clay where the penetration may be as low as one metre.[5]

The GPR unit sends short bursts of electromagnetic energy downward into the ground from the transmitter antenna which touches the ground. The energy is reflected back to the receiver antenna by subsurface interfaces of materials which have different electrical properties. The reflecting interfaces could be at changes in geology or buried materials such as wastes. The data are transferred to a console for storage and data processing for display. The radar reflections are displayed in a graph of time versus distance, similar to that of seismic reflection data.[5,8]

3.0 APPLICATION OF GEOPHYSICAL METHODS TO ENVIRONMENTAL PROBLEMS

3.1 MAGNETIC

Magnetic surveys are used to help resolve environmental problems where hazardous wastes are associated with ferrous metal containers. Hazardous wastes may be located directly when contained by steel drums, storage tanks, transformers etc.; or indirectly where wastes have been buried with other metallic objects which act as a tracer for the wastes. Magnetic surveys may be used to help enforce municipal bylaws by delineating illegal waste sites such as construction rubble which should have been disposed of in a landfill site. Abandoned buried pipelines or wells which have not been properly sealed may transport contamination from the source area to non-contaminated areas or aquifers. Magnetometers can also be used to improve safety during site assessments by selecting drilling areas where there are no buried drums or storage tanks and thus avoiding further contamination and or health risks.

3.11 Advantages of Magnetic Surveys

1. Continuous recording instruments, referred to as walking magnetometers or gradiometers, can cover large areas quickly allowing for closer line spacing and thus better resolution of the anomalies.

2. Total field data can be interpreted both quantitatively and qualitatively. Computer interpretation software, such as Gridepth®, by Geosoft, allows for three dimensional analysis of the anomalies by selecting anomalies based on the percent error in the x,y and z dimensions.

3. The portability of magnetometers allows for data to be recorded over rough or wooded terrain, especially in manual modes.

4. The gradient data do not require correcting as a result of daily changes (diurnal variations) in the earth's magnetic field.

3.12 Disadvantages of Magnetometer Surveys

1. The magnetic intensity of anomalies may vary depending on the orientation of the object.

2. Ferromagnetic debris or other culture sources such as fences, steel pipe lines, buildings and live electrical wires may make anomalies difficult or impossible to interpret.

3. Magnetometers only respond to ferrous metals and not to such metals as aluminum, brass, tin and copper.

4. Under some conditions, due to the daily fluctuations in the earth's total magnetic field, the total field data may require corrections.

3.2 ELECTROMAGNETIC (Frequency Domain)

Electromagnetic surveys can map any natural or contaminant feature which provides sufficient contrast in terrain conductivity as compared to background values and lies within the depth penetration of the instrument. Sufficient contrast is variable depending on the terrain conductivity of the background but it should be large enough that it stands out from the background conductivities. At some sites, there may be two or more areas with distinctly different background values as a result of geology or depth to water table. If these areas are large enough, each area may be interpreted separately for anomalous values. An example of this is in Figure 20 where the water table varies significantly above and below the bluff separating the contaminant plume. Naturally occurring terrain conductivity contrasts in the earth are due to porosity, soil moisture content, clay content and conductivity of the soil water.

Contaminant plumes may be caused by either organic or inorganic sources. Organic sources such as gasoline are resistive and are very difficult to map. The plume is likely to have only a small terrain conductivity contrast with the background geology. It is important when mapping organic plumes that the geology be uniform and that the area be free of culture sources which may cause instrument noise. Inorganic plumes are conductive and usually provide a much greater contrast in terrain conductivity with the background geology than do organic plumes. Changes in terrain conductivity in inorganic contaminated areas are due to an increase in the total dissolved solids (TDS) in the water content in the soil as a result of leaching or direct liquid disposal in the soil. McNeill[18] states that with the addition of approximately 25 ppm of TDS to the soil water, the bulk soil conductivity will increase by approximately 1 mS/m. Two of the principle applications of electromagnetic surveys are contaminant plume mapping and locating buried hazardous wastes. The basic survey method is to record the data over the suspected contaminated area making sure to include sufficient background areas (ie. areas not contaminated) to provide good resolution of the waste site or plume boundaries. The terrain conductivity values are recorded either along profiles or on a grid pattern. It should be noted,however, that with the use of geophysical methods, mapping the full extent to the contaminant plume will not likely be attained. Geophysical mapping is only a tool that provides guidance to the hydrogeologist in showing direction, minimum extent and in some cases some information as to the depth of the plume. This information can then be used by the hydrogeologist in the designing of the monitoring well network.

A summary of the various applications of electromagnetic surveys are as follows:

1. Contaminant plume mapping of landfill sites. The map of the contaminant plume can be used to optimize the design of a monitoring well network for an existing landfill or it could be used to assess an existing monitoring well network to determine if there are anomalous areas not monitored. The conductivity map will show shallow groundwater flow direction and may indicate whether the landfill is out of compliance regarding property boundaries.

2. Salt contamination plumes either from storage facilities or from road salting operations. By mapping the direction and measurable extent of the salt contamination the information can be used to help determine the responsible party for contamination and assess which down gradient wells are or may become contaminated.

3. Other types of inorganic plumes that can be mapped are industrial plumes due to acids or bases, mine tailings, fertilizer and sewage lagoons.

4. There are some case histories published where electromagnetic surveys has been used to map organic plumes. Organic plumes consist of two different types, hydrocarbon (LNAPL) which float on top of the watertable and heavy organic contaminants (DNAPLs) which sink. In either case, the organic material reduces the conductivity with respect to background. Data interpretation is difficult since the effect of the organic contaminants will likely be small compared to possible changes in geology.

5. Electromagnetic surveys can also be used to locate former landfill sites (which may no longer resemble landfill sites due to changes in use), as well as to locate illegally buried wastes which should have been sent to a landfill.

6. Undulating bedrock within the penetration of the instrument can be mapped provided there is a good contrast between the bedrock and the surrounding geology. Buried bedrock channels may change normal groundwater flow directions and therefore knowing the location of these channels would be crucial in designing the monitoring well network.

7. VLF has been used to map groundwater aquifers associated with vertical bedrock fractures and geological faults and therefore may have some application in mapping such formations should they become contaminated.

8. The EM-31 Conductivity Meter, when measuring the inphase component of the induced magnetic field, can detect buried metals such as drums, storage tanks, reinforced concrete foundations, pipes and other metallic debris.

3.21 Advantages of Electromagnetic Surveys

1. Large areas can be covered quickly with sufficient detail so that good resolution of the contaminated area can be made.

2. Because of electromagnetic induction there is no surface penetration, such as the electrodes in conventional resistivity profiling; data therefore can be recorded over asphalt, concrete or very resistive ground.

3. The effective depth of penetration is controlled by the instrument mode (vertical or horizontal dipole) and intercoil separation. By using a combination of EM-31 and EM-34 instruments, depth profiles from 3, 6, 15, 30 and 60 metres may be obtained.

4. The EM-31 Terrain Conductivity Meter can measure both the quad-phase and inphase component at the same time with the use of a data logger. This has an advantage in some situations where a general assessment of a site is being carried out such as in decommissioning.

5. Both ferrous and non-ferrous metals can be detected when operated in the inphase mode.

3.22 Disadvantages of Electromagnetic Surveys

1. The instruments do not respond well in highly resistive formations (ie.> 1000 ohm-metres).

2. There are depth limitations compared to conventional resistivity methods.

3. EM methods can be sensitive to noise from power lines, radio transmitters, buildings, vehicles, machinery, buried metal, buried metal pipes, cables and metal fences.

3.3 VLF RESISTIVITY

VLF resistivity surveys can be used to map changes in the earth's resistivity and are especially effective in areas where the surface resistivity is high and where there is an elongated conductive area at depth which channels the current flow. The VLF resistivity survey can be used to locate conductive bodies such as contaminant plumes and buried channels in resistive bedrock. VLF resistivity surveys are an alternative method to other types of EM surveys for contamination plume mapping.

3.31 Advantages of VLF Resistivity Surveys

1. The instrument works well in high surface resistivity areas.

2. A VLF resistivity survey can be carried out by one person provided the stations have been previously marked, making the surveys fast and economical compared to conventional resistivity methods.

3. The method provides good lateral and vertical resolution of 2 layers provided either the thickness of the first layer or resistivity of one of the layers is known.

4. The phase-angle provides information which determines whether the earth is homogeneous or layered and whether the resistivity is increasing or decreasing for the depth of penetration.

5. The instrument can be used effectively in wooded areas or where there is limited space.

3.32 Disadvantages of VLF Resistivity Surveys

1. The depth of penetration is variable depending on the earth resistivity. The greatest penetration is in resistive areas and the lowest penetration is in conductive areas.

2. There will be some error in apparent resistivity values recorded in and adjacent to areas where there are substantial changes in near surface resistivity.

3.4 GROUND PENETRATING RADAR

Ground penetrating radar units have many applications in both geological mapping and in investigating hazardous waste sites. GPR is most effective in resistive soils where it can be used to map depth to bedrock and water table elevations. In bedrock, GPR has been used to map fractures and measure changes in bedrock type. In winter, GPR has also been used on frozen lakes to map lake bottom sediments. At hazardous waste sites, GPR has been used to map contamination plumes and locate buried wastes such as drums and tanks. It can also locate both metallic and non-metallic pipes.

3.41 Advantages of Ground Penetrating Radar

1. The method provides continuous high resolution data.

2. Frequency of operation can be adjusted to site conditions. High frequency provides the best resolution while lower frequency provides deeper penetration.

3. Can be used inside buildings or along the outside of building foundations.

4. Can be used through ice to map depth profiles of water and sediments.

3.42 Disadvantages of Ground Penetrating Radar

1. Wet clay formations severely limit penetration of GPR.

2. The penetration is site specific depending on the geology.

3.5 SUMMARY

The four geophysical methods described are the chief methods used in helping resolve environmental problems concerning buried hazardous wastes and contaminant plume mapping. In some cases, more than one method may be applicable for resolving a particular problem. Some of the parameters to consider when choosing the geophysical method are geology, the type of contaminant, depth penetration required to measure the contaminant as well as availability of the equipment, cost of purchase or rental, and personal preference and experience of the investigator.

The depth of investigation will have some bearing on the difficulty of data interpretation. In general, the deeper the measurement, the more difficult the interpretation due to such parameters as signal strength, and increasing complications related to geologic layering and the likelihood of multiple target responses.

The survey design and procedures will also vary depending on the type and purpose of the survey. Choosing line spacings and recording intervals along the lines is a decision which is always site specific. The line spacing and interval along the line make a data grid which should be small enough so that the target will not be missed. Some of the parameters which decide these spacings are:

<u>For Locating Buried Metals</u>

1. The size, shape and configuration of the target.

2. Depth of the target.

3. The lateral resolution of the instrument being used.

4. How clean the site is from noise.

   (Noise is the response from any source other than the target which may totally or partly camouflage the response from the target being sought. If the target is suspected near an area of interference, a more detailed grid may help distinguish between the unwanted interference responses and the response from the target.)

5. The length of the target.

   For long targets like pipes, the line direction, where possible, should be perpendicular to the target. This is especially true for instruments using data loggers. In situations where there is a pipe close to a building foundation, a close grid parallel to the building may produce better results.

For Mapping Contamination Plumes

1. The size of the plume.

   Need sufficient data points to define the edge of the plume. If too large a grid is used a small plume may be missed or the plume will appear larger than it actually is due to interpolation between the data points. It is sometimes necessary to reduce the grid spacing to ensure location accuracy near the edge of the plume or to delineate the anomalous effects due to changes in geology or other sources of interference.

2. The length of the plume.

   If the plume is elongated, and the geology is uniform, the line spacings which are perpendicular to the plume may be increased. The normal data interval should be maintained to delineate the edge of the plume.

4.0 CASE HISTORIES

4.1 MAGNETIC

The following case histories illustrate the use of magnetics for locating buried drums, fuel tanks, pipe lines and well casings. In the first case history, drums were buried at a depth of less than 2 metres in a relatively clean environment (ie. little or no scrap ferrous metal buried with the drums). In the second case, drums were buried or covered with fill material mixed with scrap metal up to depths of 4 metres. In the third case history, the magnetic response obtained from wells, a 4 inch metal gas line and a 1000 gallon fuel tank is shown and finally, the fourth case history compares the magnetic anomalies of fuel tanks, at five different sites, illustrating how the magnetic response from fuel tanks varies with size and orientation.

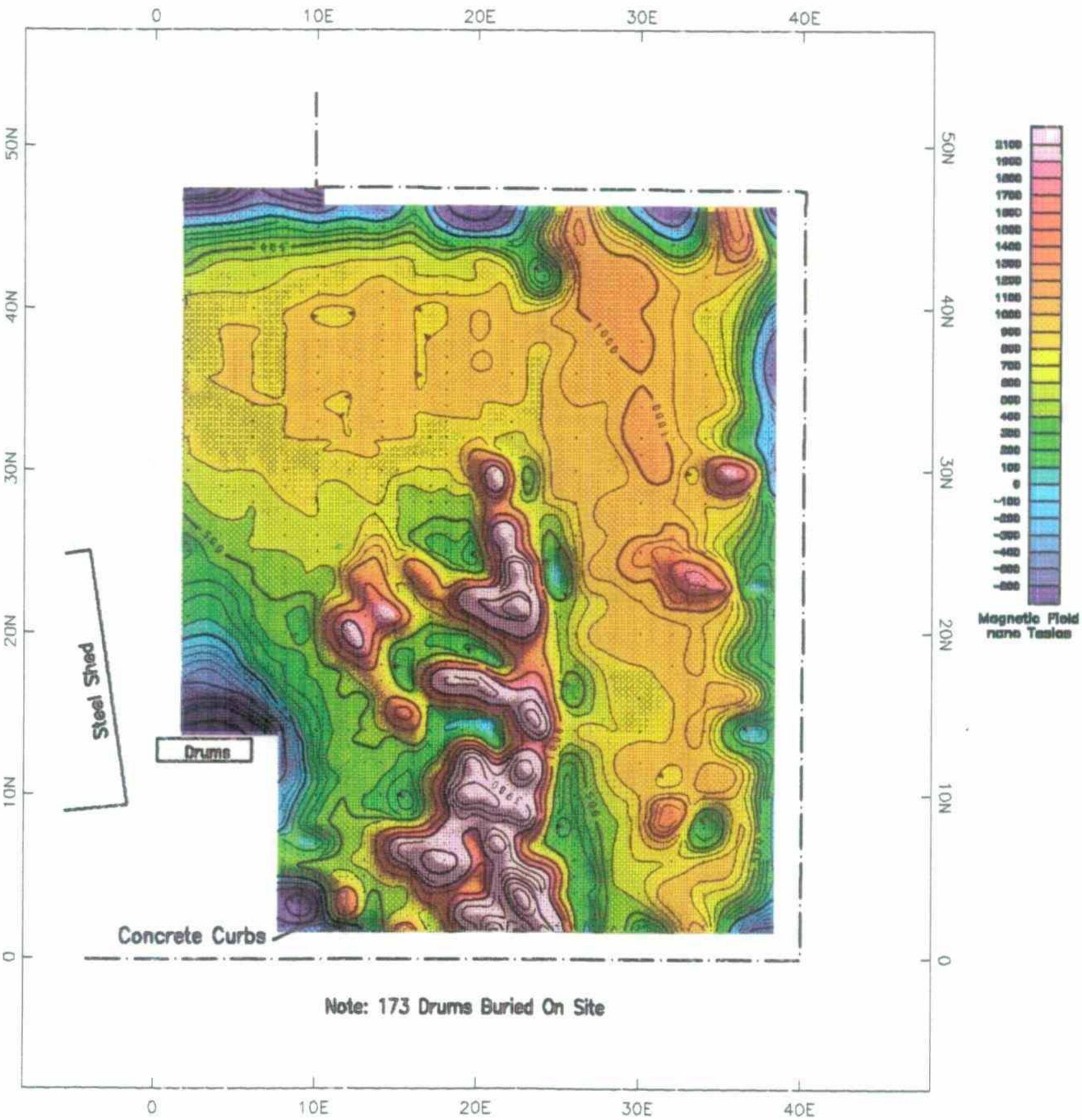
4.11 THE LOCATION OF BURIED DRUMS AT A DEPTH OF LESS THAN TWO METRES AT A SITE IN TRENTON

The survey was carried out to investigate the allegations that drums containing hazardous wastes had been buried on the site of a factory in Trenton. The burial of such wastes would have threatened the quality of the groundwater in the area and would have been illegal.

The area of investigation was about 40 by 50 metres and mainly free of scrap metal on the surface. Metallic objects which would interfere with the magnetic field responses were a chain link fence around three sides of the area, a steel shed, a stack of drums on the surface and concrete curbs (shown in Figure 2).

The instrument used for the magnetometer survey was the McPhar M700 Magnetometer. This instrument is a vertical field flux gate magnetometer where the vertical magnetic field is recorded relative to a base reading chosen by the operator. In this case the base reading was 1000 nano Teslas. The survey was carried out by reading the vertical magnetic field on a two metre grid decreasing to a one metre grid over the main anomaly.

The results of the survey are shown in Figure 2. The surface metallic objects ie., fence, surface drums and steel shed created a negative metallic field relative to the base reading of 1000 nano Teslas. The pile of concrete curbs created a dipole anomaly with both positive and negative poles. The areas where metallic metals were buried are generally outlined by the 1000 nano Tesla contour. The excavation of these anomalies revealed 173 drums buried about 1 metre deep. The drums contained PCB contaminated oil and solvents.



MAGNETOMETER SURVEY (TRENTON)

MAGNETIC ANOMALIES OF BURIED DRUMS

FIGURE 2

KF, MOE, 1998

4.12 THE LOCATION OF BURIED DRUMS AT DEPTHS UP TO FOUR METRES ON THE A SITE IN ELMIRA

BACKGROUND

A magnetometer survey was carried out to investigate allegations that drums had been buried on the site. There was concern that drums containing hazardous chemicals would contaminate Elmira's groundwater supply. The site consisted of an area about 120 by 200 metres. Most of the area had been used as a disposal site for fill excavated locally from buildings, sewers etc. The fill in some areas was as deep as 4 metres. In addition to fill there was also a lot of scrap metal distributed around the site. The north-east area of the site had been used for disposal of asphalt and concrete, some containing reinforcing rods. Since there were various types of scrap metal on the surface it was assumed that scrap metal would also be buried. This made estimating a range for the noise level impossible since neither the type of object or depth of burial was known. The southern half of the site was used to store drums and fuel tanks as well as other metal containers. Some of these can be seen in the photograph taken below on April 4, 1988.

Figure 3. Photo of Elmira Site looking west taken on April 4, 1988 by R. Johnson, IEB.

1990 MAGNETOMETER SURVEY

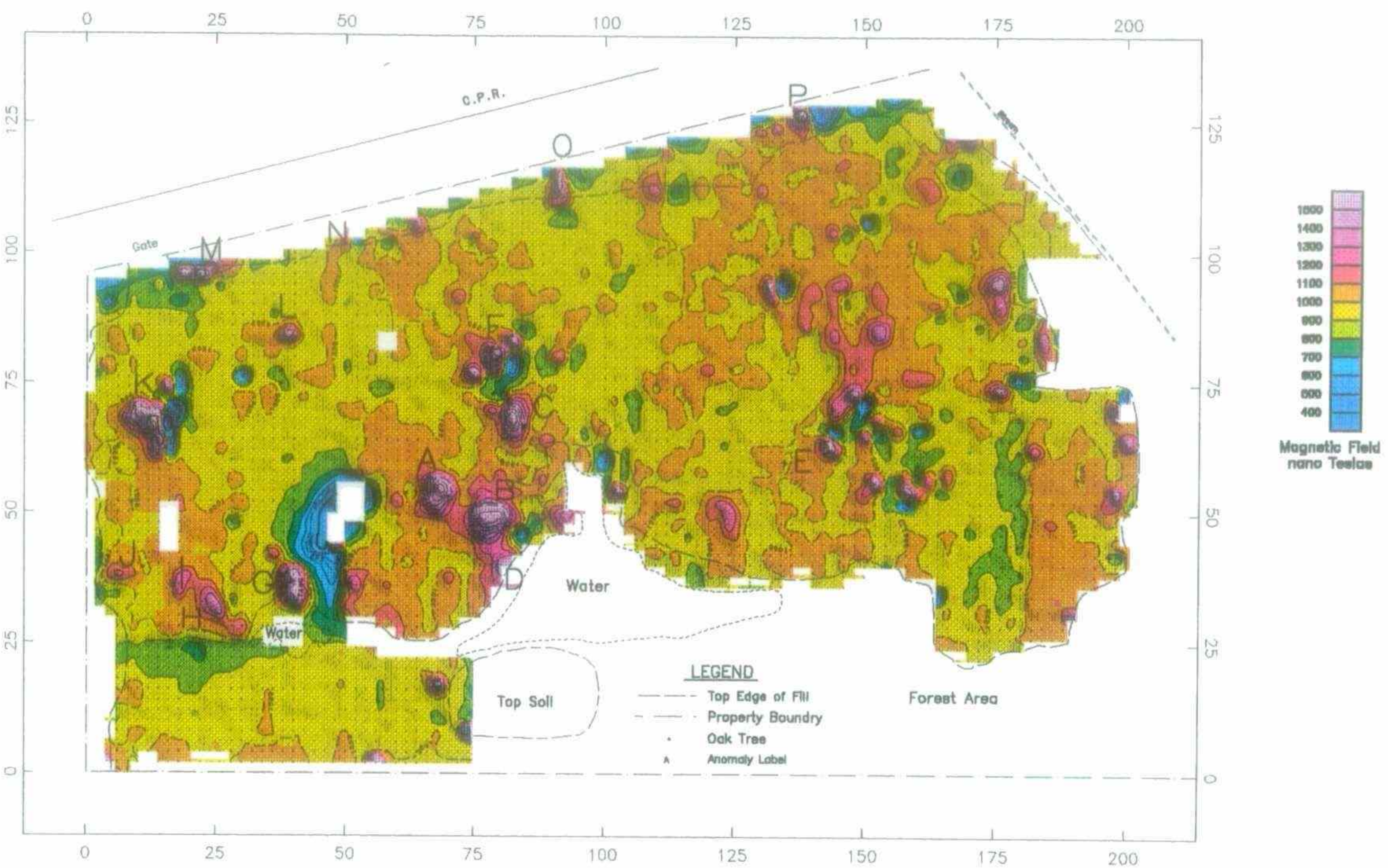
The initial magnetometer survey was carried out in 1990 using the McPhar M700 magnetometer. This survey was carried out on a two metre grid. The data were analysed manually and 16 anomalies were selected for excavation, mostly from the southern half of the site. Because the southern half of the site was used to store drums, that area was deemed as having a greater potential for buried drums. Although there were also many anomalies on the northern section of the site, the surface scrap metal made the selection of anomalies for excavation more difficult. From the 16 anomalies selected 8 of the anomalies contained a total of 47 drums, some of which contained solvents. The anomalies excavated are shown in Figure 4. This computerized map of the anomalies was not available at the time of excavation.

In the initial survey, the field data were recorded to the closest 50 nano Teslas, the practical maximum recording sensitivity of the instrument for large survey areas. The data were plotted manually and the anomalies selected for excavation were in the order of 200 nano Teslas or greater. It was acknowledged that a single drum, if buried deeper than 2 metres, would likely be missed but groups of drums would likely be located within this range. Due to the importance of this issue, it was requested that a more sensitive survey be conducted with the latest geophysical equipment. In 1994, two duplicate surveys of the area were conducted using the GEM, GSM-19 Walking Gradiometer and the Geonics EM61 Metal Detector.

1994 GRADIOMETER SURVEY

The Walking Gradiometer has two sensors mounted on a packframe and each sensor records the earth's total magnetic field simultaneously. The data output from the instrument is the total magnetic field value in nano Teslas and the gradient value in nano Teslas/metre. The gradient value is calculated by using the difference in the total magnetic field values recorded at the two sensors divided by the distance between them.

The field procedure consisted of recording the total magnetic field data at one second intervals along grid lines spaced two metres apart. Distance checks were made at 5 metre intervals, using a flagged tape for control. When the data were later analysed on the computer, a linear interpolation of all data recorded between the 5 metre check points was made, assigning a distance value for each point. Depending on the walking pace, the recording intervals were in the range of 0.8 to 1.0 metres.



1990 MAGNETOMETER SURVEY AT ELMIRA SITE

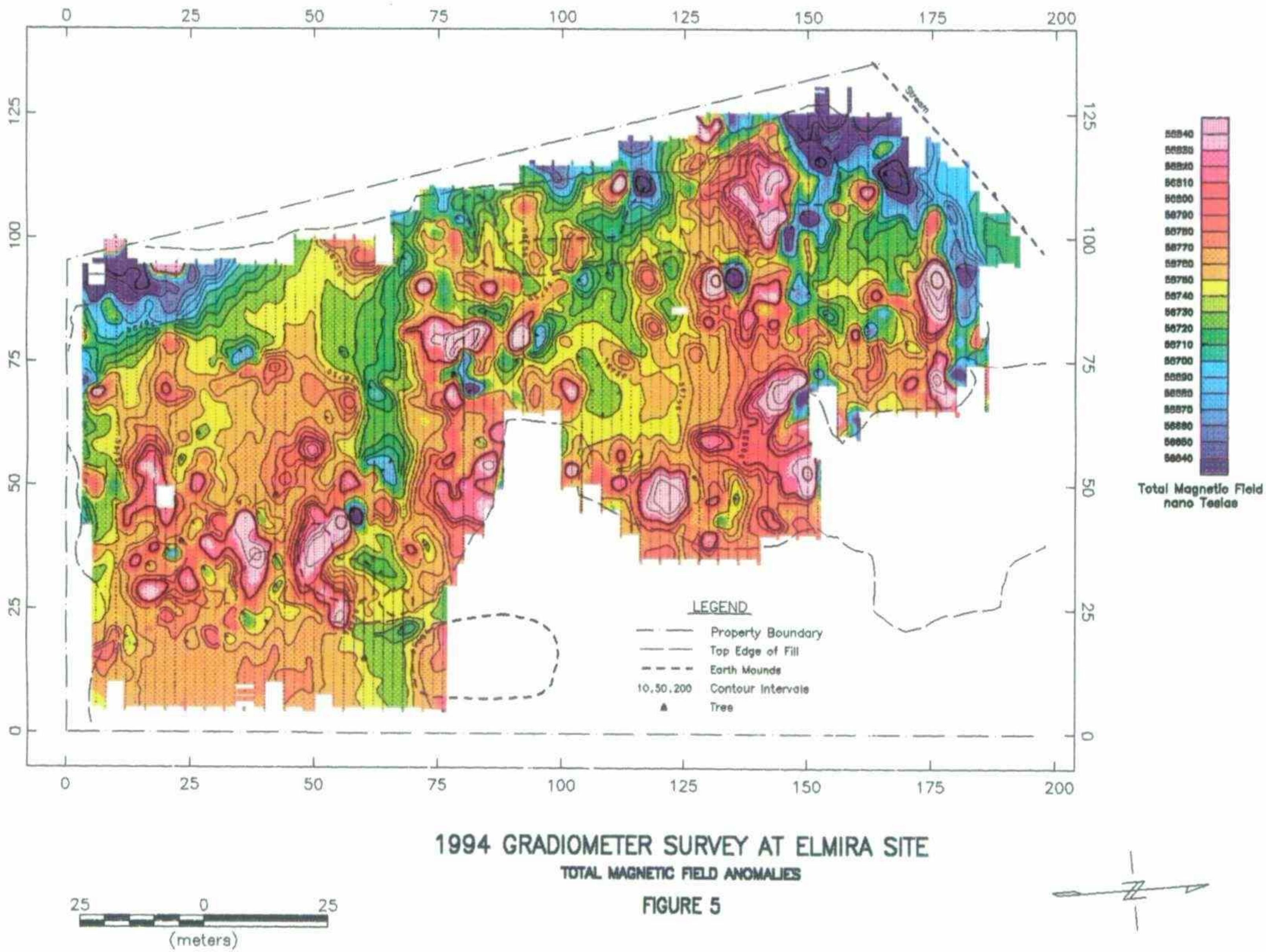
VERTICAL FIELD ANOMALIES

FIGURE 4

25 0 25

(meters)

KF, MOEE, 1997

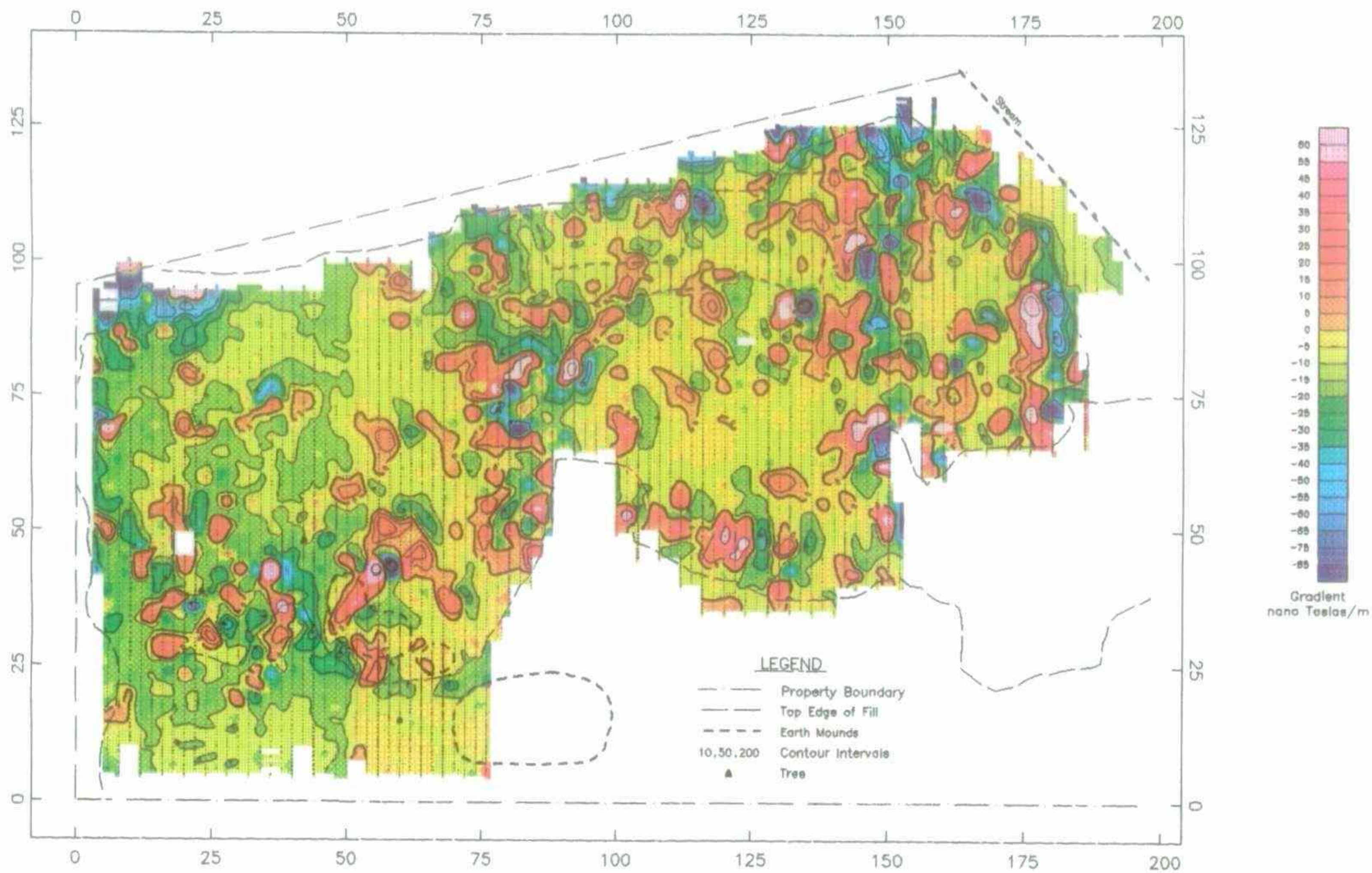


1994 GRADIOMETER SURVEY AT ELMIRA SITE

TOTAL MAGNETIC FIELD ANOMALIES

FIGURE 5

KF, MOEE, 1997



1994 GRADIOMETER SURVEY AT ELMIRA SITE

GRADIENT ANOMALIES

FIGURE 6

25 0 25
(meters)

KF, MOEE, 1997

The total magnetic field data are shown in the form of a colour contour map in Figure 5. The background reading for the earth's total magnetic field at this site was 56,750 nano Teslas. Since all the large anomalous areas were previously excavated from the 1990 survey, only anomalies in the range of 200 nano Teslas or less remained. Within this range of anomalies, the expectation was that there may be single drums or possibly, a small group at depth where induced and permanent fields subtracted from each other, due to their orientation, thus giving a much smaller than expected response. The gradient data is shown in Figure 6. The gradient data eliminate any time variations in the data or effects from magnetic storms. This information is useful in helping estimate the depth of the anomalies since shallow anomalies produce high gradients. Because of the number of anomalies due to the scrap metal on the site, a more advanced approach to data interpretation was required to locate possible drums. To do this, the computer program called GRIDEPTH® was used to select potential anomalies which could be caused by drums.

GRIDEPTH®

The following is a very brief outline of the method to illustrate its use and not intended as a manual on how to use the program. The GRIDEPTH® program[14] uses the Euler deconvolution process which requires the following four grids as input data:

1. T = The total magnetic field
2. dT/dx = The first derivative in the X direction
3. dT/dy = The first derivative in the Y direction
4. dT/dz = The first derivative in the Z direction

The four grids are usually calculated from the total magnetic field grid.

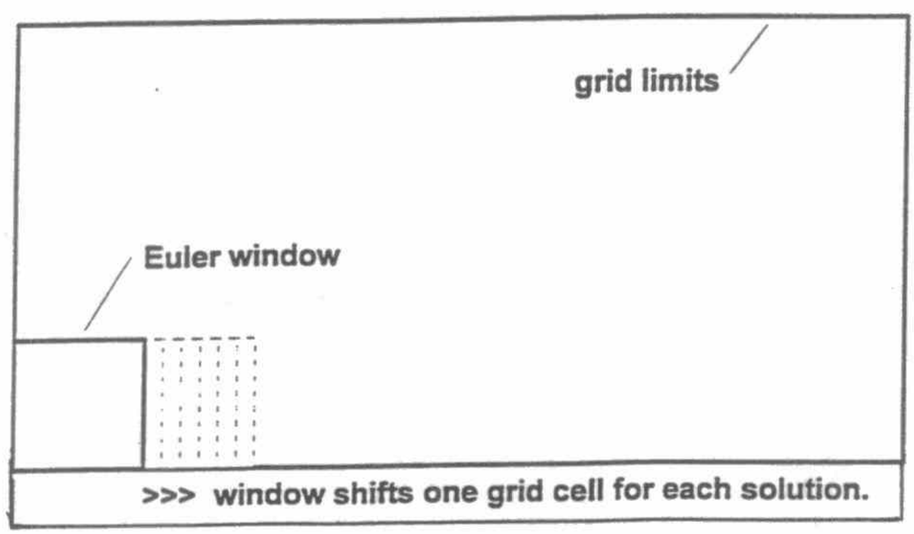


Figure 7. Euler Window For Calculation Of GRIDEPTH® Solutions.[14]

In general, a cell size for the total field data is chosen which is not less than the spacing between the data points along the lines. As illustrated in Figure 7, a Euler Window[14,33] size is chosen (usually 10 by 10 grid cells in size). The size of the window is chosen so that within the window there is substantial variation of the field and field gradients, but small enough to basically include significant effects from only single sources. For this survey, the cell size was chosen as 0.8 metres making a window size of 8 by 8 metres. For each Euler Window, the GRIDEPTH® program applies Euler deconvolution by using the data extracted from the square window from each of the four input grids. The window is then shifted one grid cell and the process repeated to calculate a new solution. After the window has crossed the first row of grid cells, the window shifts up one cell at the left side and again proceeds as before calculating solutions with the window shifting one cell at a time across the survey area. The solution calculated is the distance (x,y and z) expressed as a percentage of error to the target from the centre of the window. Since a high number of solutions are calculated, the only solutions saved are those that are less than the limit specified by the user (ie less than 20% or 10% etc.).

To further define the type of source that is being selected, the structural index[14,33] parameter is applied. The structural index is defined as a measure of the rate of change with distance of the magnetic field. Since the rate of change is different for various sources, using the correct structural index for the target sought (like a drum) will result in a more accurate solution for that type of target. Structural indices[33] for a sheet, a vertical drum and a tank are 1.0, 2.0 and 3.0 respectively. The correct structural index is the one which produces the closest cluster of solutions for a given target. Figure 8 illustrates the best solution for a vertical pipe. In this survey, structural indices of 2.5 and 3.0 were tried with 2.5 giving the best results.

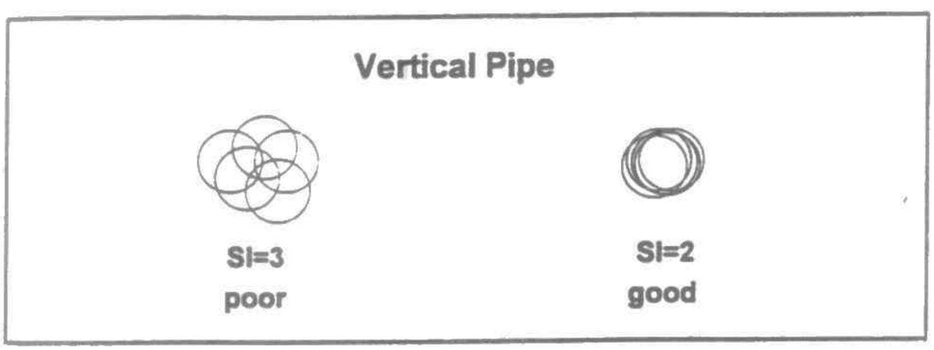
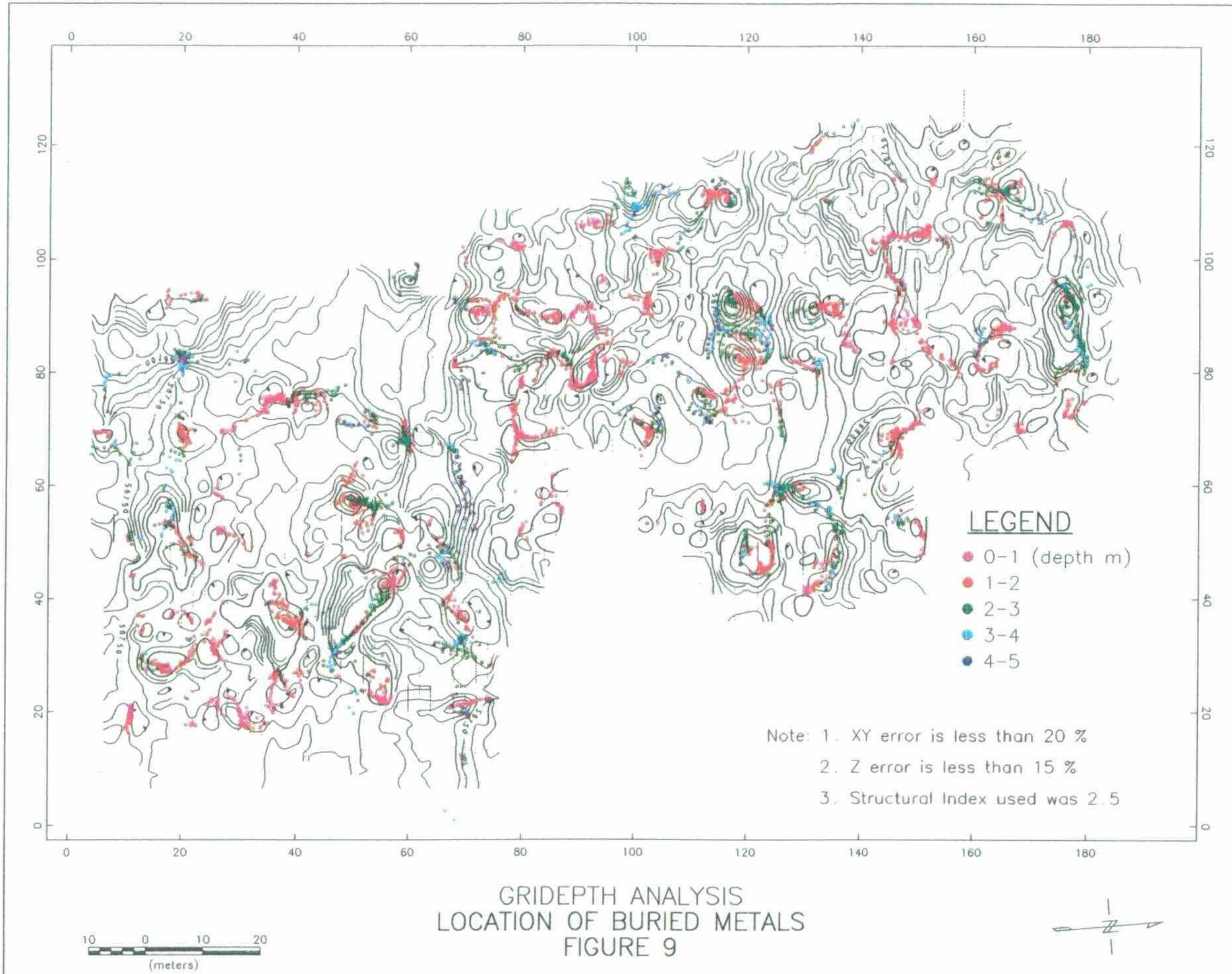
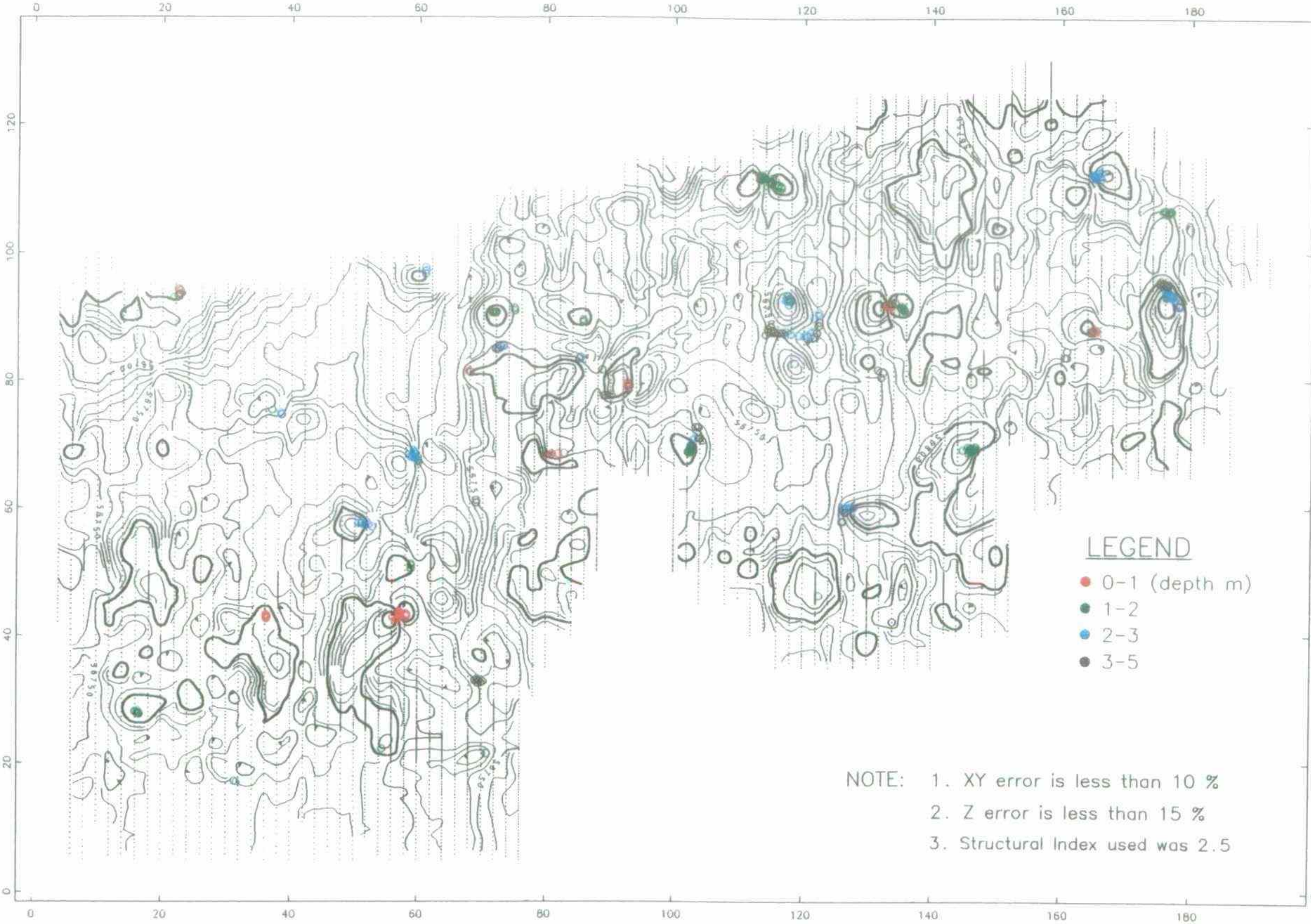


Figure 8. Shows comparative GRIDEPTH® Solutions using different Structural Indices for a Vertical Pipe (from Reid, 1990).



GRIDEPTH ANALYSIS
LOCATION OF BURIED METALS
FIGURE 9



GRIDEPTH ANALYSIS
LOCATION OF BURIED METALS
FIGURE 10

10 0 10 20
(meters)

KF. MOEE, 1997

Each solution calculated within the limits specified is plotted on a map as a circle. Areas which have a number of solutions superimposed on top of each other indicate the highest degree of accuracy for that target. The procedure used in this survey was to first select all solutions in the X and Y directions that had a percent error of less than 20 percent. The next step was to select the same XY parameters and add the depth parameter with a percent error of less than 15 percent. In Figure 9, these solutions are shown. The depths to the solutions are also shown in the colour coded legend. Some of the solutions are tightly clustered while others are not. To increase the location accuracy of the solutions further restrictions on the XY error was necessary. Figure 10 shows the final map of GRIDEPTH® solutions using a XY error of less than 10 percent and a Z error of less than 15 percent. The depths to these solutions are shown in the legend.

EM-61 METAL DETECTOR

The EM-61 is a high sensitivity, high resolution time-domain metal detector which can detect both ferrous and non-ferrous metals.[13] The instrument consists of a transmitter coil with coincident receiver coil, a second receiver coil, a backpack with battery power and processing electronics and a digital data recorder. The transmitter and receiver coils are one metre square and can either be carried, suspended from a belt harness or mounted on a cart. The upper receiver coil and the lower coincident receiver/transmitter coils are spaced vertically by 40 cm with a distance of 45 cm maintained between the ground and the lower coils.

The EM61 generates electromagnetic (EM) pulses 150 times per second and measures during the off-time between pulses. After each pulse, secondary EM fields are induced briefly in moderately conductive earth and for a longer time in the metallic targets. Between each pulse the EM61 waits until the response from the conductive earth dissipates and then measures the prolonged buried metal response. The response value is in millivolts (mv).[13]

For data interpretation, the data from the top and bottom receiver coils are referred to as channel T and channel B respectively. The differential channel is calculated automatically from the following formula:

$$D = k^*CH\ T - CH\ B$$

where D is differential output in mv
CH T is output from top coil in mv
CH B is output from bottom coil in mv
k is depth coefficient normally set to 1

By comparing the response from channel B and the differential channel, many anomalies due to surface scrap metal can be eliminated. Channel B contains information from all targets within the reach of the EM-61 while the differential channel shows mostly deeper targets and suppresses response from near surface material. An apparent depth to buried targets can be calculated using the computer program Dat61. This calculation is based on the ratio of amplitude from channel T and channel B response. The calculation of apparent depth is an approximation, which is usually slightly deeper than the actual depth.

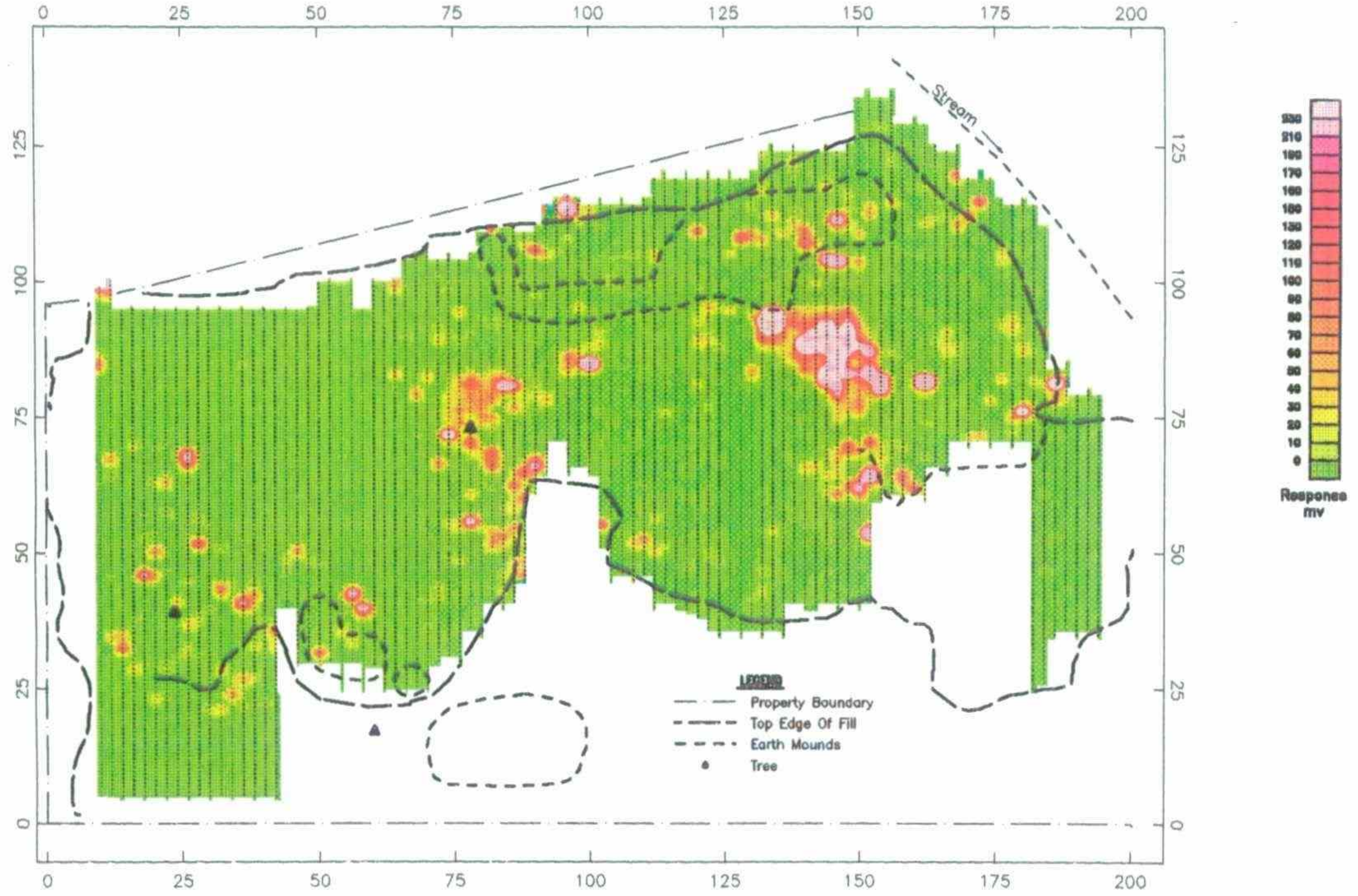
EM-61 SURVEY

On the Elmira site, the EM-61 could not be trailer mounted due to the ruggedness of the terrain and the snow depth. The southern third of the site was investigated in winter although the survey had to be terminated due to snow depth and continued in the spring. The survey was conducted in the manual mode by taking readings about every 0.833 metres along the grid lines with distance checks at 5 metre intervals. The survey lines were spaced at 2 metre intervals which is the maximum spacing that should be used with this instrument since it has an extremely high lateral resolution. The grid lines were essentially the same as used in the walking gradiometer survey.

EM-61 SURVEY RESULTS

In Figures 11 and 12, the anomalies from the EM-61 data for channel B and the differential channel are shown. The interpretation of these anomalies involved viewing the anomalies in profile on the computer and using the Dat61 program to calculate an apparent depth to target. The apparent depth and the response values were then compared to Figure 13 which shows a graphical response with depth for a 55 gallon steel drum. From the EM-61 data interpretation, 33 anomalies were selected as having the potential to be caused by a steel drum (ie. all targets that could be caused by a single 45 gallon drum or larger were selected).

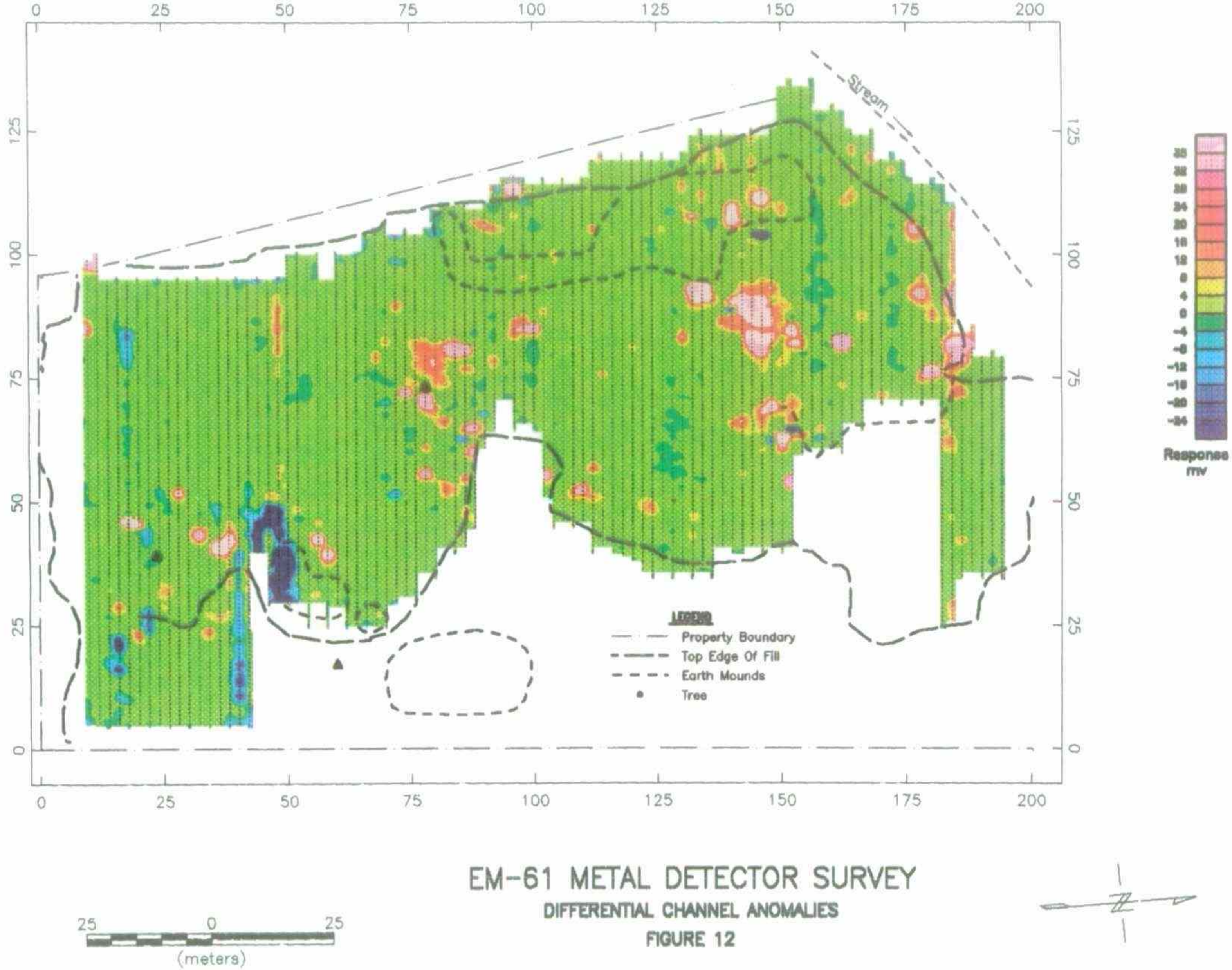
Note:
During the EM-61 survey, a noise problem occurred with the top channel data. Two possible causes could be that the back pack was at times to close to the top channel receiver coil or there may have been some moisture in the connectors. The transmitter and receiver coils had to be carried since the terrain was to rugged for them to be cart mounted. Offset corrections were made to the top channel data, however, in doing so, some negative values were created in the differential channel data as can be seen in Figure 12. This problem was worse in the first half of the survey which was conducted during the winter.



EM-61 METAL DETECTOR SURVEY
CHANNEL B ANOMALIES
FIGURE 11

25 0 25
(meters)

KF, MOE, 1998



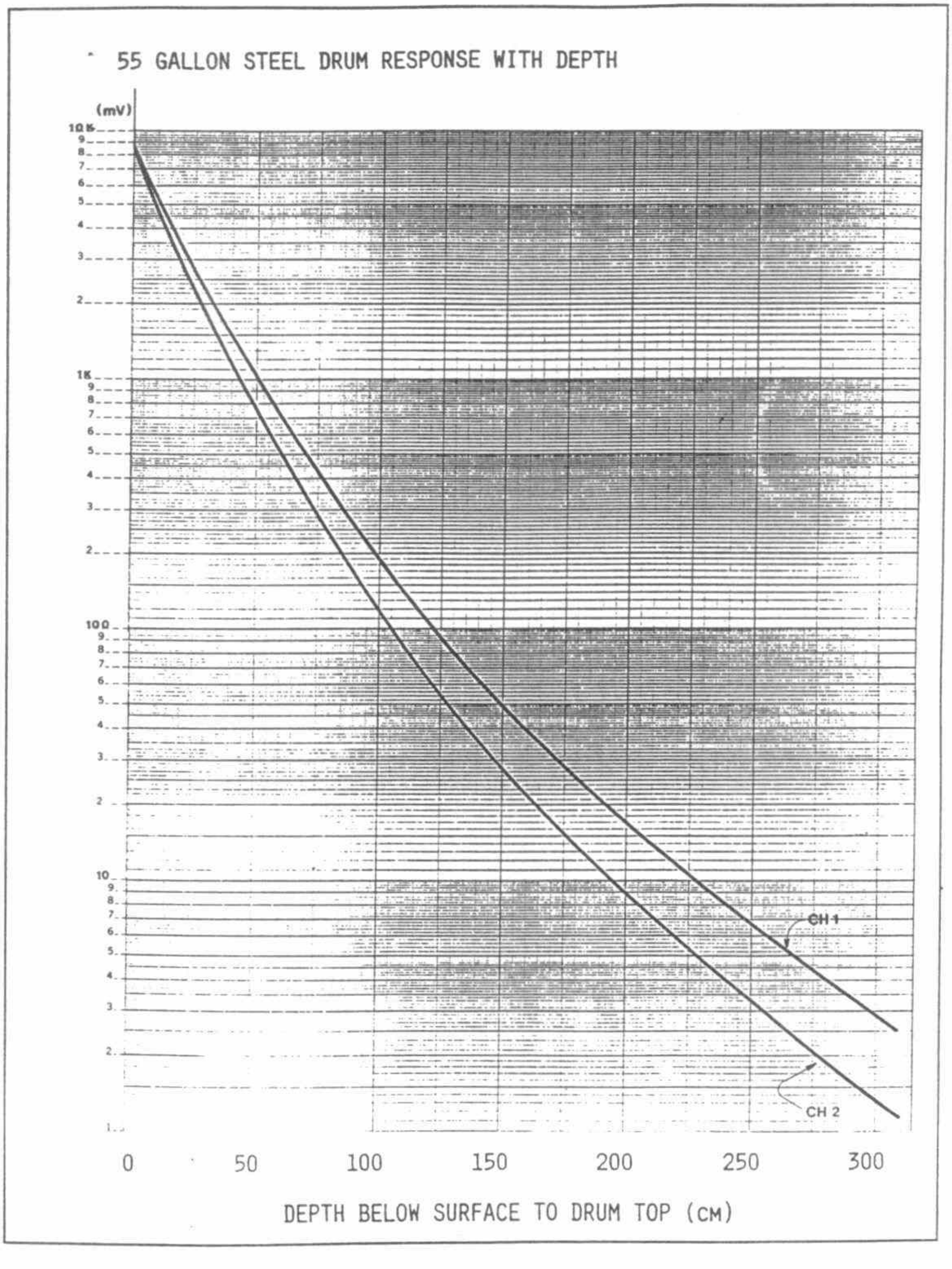
EM-61 METAL DETECTOR SURVEY

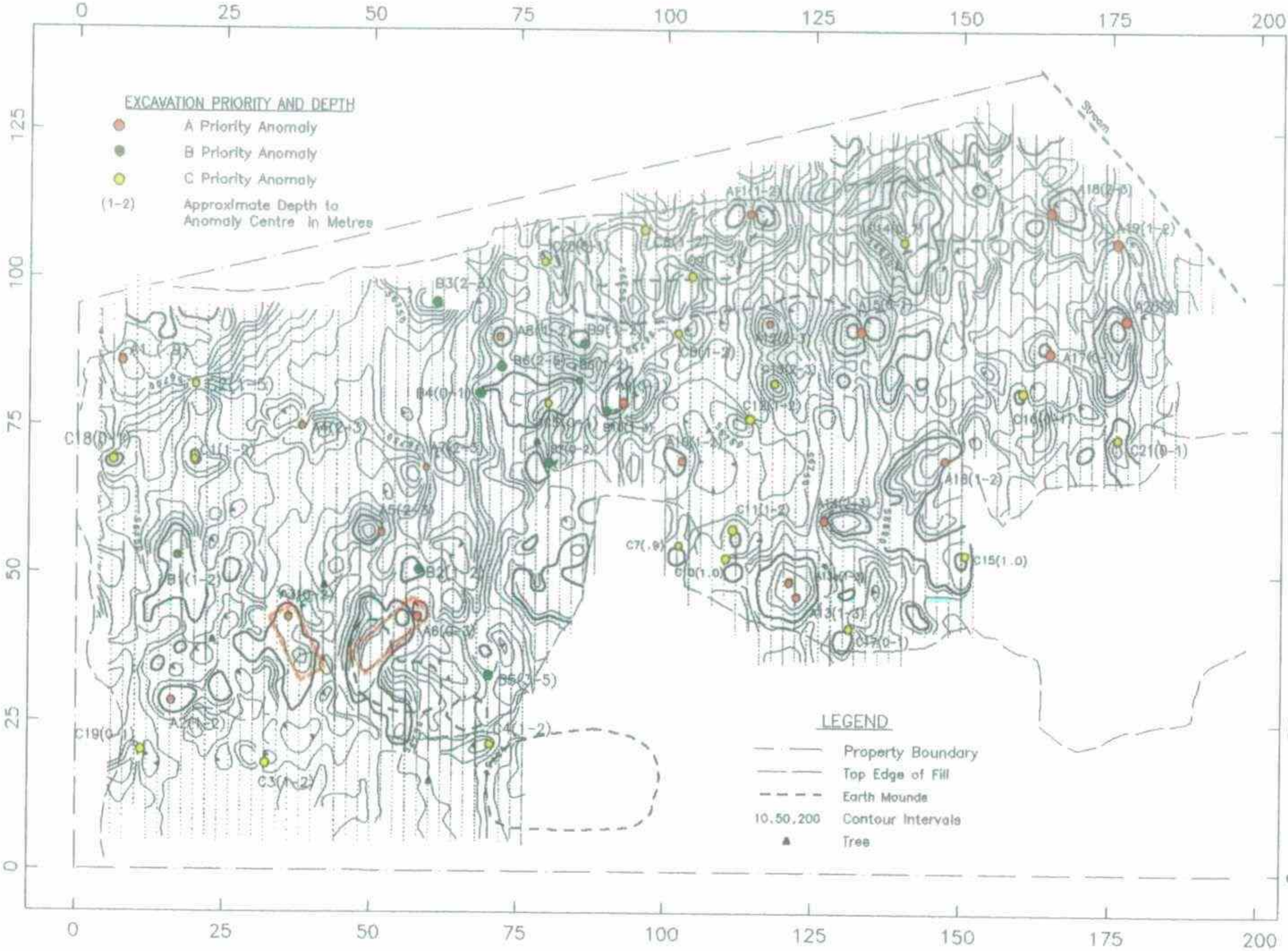
DIFFERENTIAL CHANNEL ANOMALIES

FIGURE 12

KF, MOE, 1998

Figure 13. Response From EM-61 Metal Detector with Depth for a 55 Gallon Steel Drum.[13]

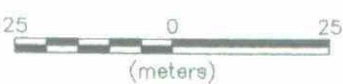




SUMMARY OF 1994 PRIORITIZED ANOMALIES

LOCATION AND DEPTH RANGE FOR EXCAVATION

FIGURE 14



KF, MOEE, 1997

SUMMARY Of GRADIOMETER AND EM-61 SURVEYS

The anomalies from the gradiometer survey selected with the GRIDEPTH® program and the 33 anomalies selected from the EM-61 data were summarized into a total of 51 anomalies to be investigated. Three levels of priority, A, B and C, were assigned for the purposes of excavation base on the likelihood that the anomaly was caused by a buried drum. These prioritized anomalies, showing the approximate depth expected in brackets, are shown in Figure 14. All of the above anomalies were excavated and a total of 27 drums were recovered. Of the total of 27 drums, 24 drums were in the A priority anomalies and 3 were in the C priority anomalies. Figure 15 shows the list of anomalies where drums were recovered. The other anomalies contained various amounts of scrap metal which included reinforcing rods, wire, steel strapping, steel posts, pipe, parts of culverts and paint cans.

FIGURE 15. List of anomalies which contained drums at the Elmira Site.

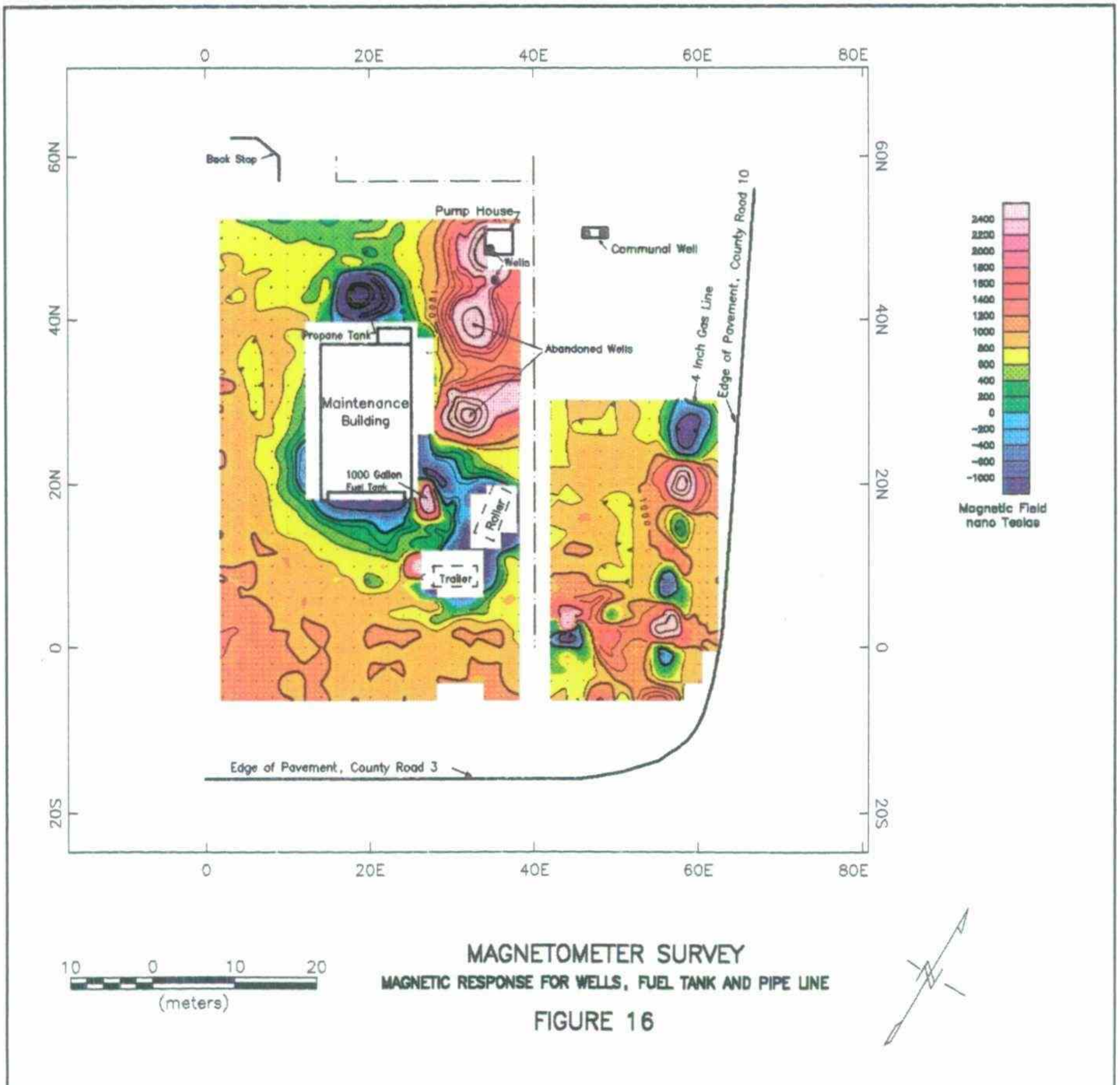
ANOMALY	DEPTH (m)	NO. DRUMS	DESCRIPTION
A2	1.0	1	empty
A3	0.3	1	empty
A8	1.3	1	empty (crushed)
A9	0.5	1	empty (crushed)
A10	2.0	2	full of contaminated water
A13	3.0	9	3 with product 3 with water 1 with paint sludge 1 with gel 1 with chemical sludge
A13a	3.0	3	1 with solvent 1 with tar and soft asphalt 1 empty
A19	1.0	2	empty (crushed)
A20	1.8	4	empty (crushed)
C1	2.0	1	contained water
C11	1.0	1	empty (crushed)
C12	1.5	1	empty (crushed)

4.13 THE MAGNETIC RESPONSE ASSOCIATED WITH BURIED WELLS, PIPE LINES AND FUEL TANKS.

In Figure 16, examples of the magnetic response from several wells, a 4 inch gas pipe line and a 1000 gallon buried fuel tank are illustrated. The magnetic response from well casings appears as a single monopole, positive anomaly. It is actually a dipole anomaly but since the casing is vertical, only the single pole is recorded. Vertical pipes or metal rods will all show as a single monopole anomaly. The examples of magnetic anomalies for wells, shown in Figure 16, are typical where there is a strong circular anomaly which decreases uniformly in all directions. The well casings have been cut off below ground surface at some unknown depth. The various wells show different strength anomalies which reflect the length and size of the casing, and the distance from the magnetometer to the top of the casing. Where the anomalies stop being circular in nature, the effects of some other metallic object is influencing the magnetic field.

The 4 inch gas pipe line shows a typical line of alternating positive and negative anomalies. This is due to the fact that the pipeline is constructed of a series of lengths of pipe attached together and each length of pipe shows a typical dipole anomaly.

The 1000 gallon fuel tank shows a typical dipole magnetic signature where the positive anomaly is located over the tank and a smaller negative anomaly is located on the north side of the tank. In this case there are also other negative anomalies north of the tank associated with surface metal near the building and the nearby roller.



MAGNETOMETER SURVEY

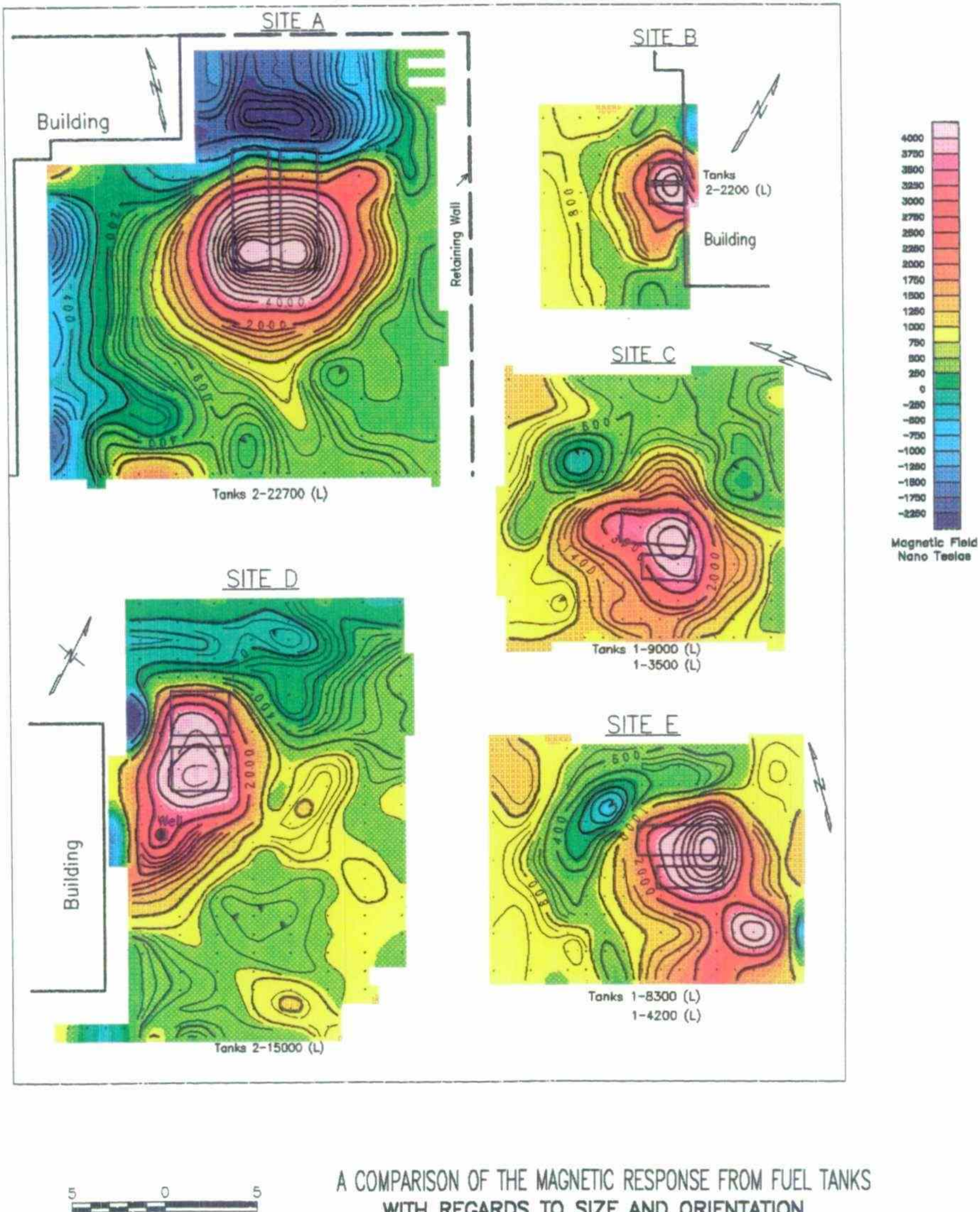
MAGNETIC RESPONSE FOR WELLS, FUEL TANK AND PIPE LINE

FIGURE 16

4.14 A COMPARISON OF THE MAGNETIC RESPONSE FROM BURIED FUEL TANKS WITH REGARDS TO SIZE AND ORIENTATION

The three main factors in determining the magnetic signature for buried tanks is the size, depth of burial and orientation. The size and depth of burial will effect maximum amplitude of the magnetic response as well as the area of the anomaly. The orientation will effect the size of the negative anomaly associated with the tank. All tanks produce a negative anomaly at the north side of the tank, however, tanks orientated in a north- south direction have stronger negative anomalies. This will be particularly true when the induced magnetic field and the permanent magnetic field are in the same direction.

In Figure 17, a composite of five sites, investigated for hydrocarbon contamination illustrates the various magnetic responses for buried fuel tanks with respect to size and orientation. At each site, the number of tanks, capacity in litres and orientation with respect to a north arrow is shown.
All of the anomalies are dipole (ie have both a positive and negative pole) however, Site A with the tanks orientated in the north-south direction has the strongest negative pole. This is partly do to the size of the tanks. In comparison, the two 15,000 litre tanks at Site D orientated generally east-west, only has a small negative anomaly to the north of the tanks. With the exception of the tanks at Site A, the tanks are located completely within the positive section of the anomaly. In Site E, the tanks are buried with other metallic rubble and both the strong negative anomaly at the north-west corner and the strong positive anomaly at the south-east sides of the tanks is due to other metallic objects.



A COMPARISON OF THE MAGNETIC RESPONSE FROM FUEL TANKS

WITH REGARDS TO SIZE AND ORIENTATION

FIGURE 17

KF, MOE, 1998

4.2 ELECTROMAGNETIC

The Geonics EM-31 Terrain Conductivity Metre is one of the most commonly used electromagnetic instruments in use today for mapping changes in ground conductivity down to a depth of about 6 metres. The following are three examples of using the EM-31 in mapping various types of contaminants ie., landfill leachate, acid sludge leachate and salt contamination. The fourth example of the use of this instrument is in mapping the location of a landfill site after it had been returned to agricultural use.

The popularity of this instrument is due largely to the ability of a single operator to measure terrain conductivity over a large area quickly. For data collection, the operate has he option to record either manually, reading directly from the instrument console, or automatically with the use of a digital acquisition system (data logger or infield computer). Digital acquisition can be either automatic, or in a manner programmed by the operator, or direct to be triggered by the operator at selected locations. A global positioning system (GPS) can be used to accurately record data locations.

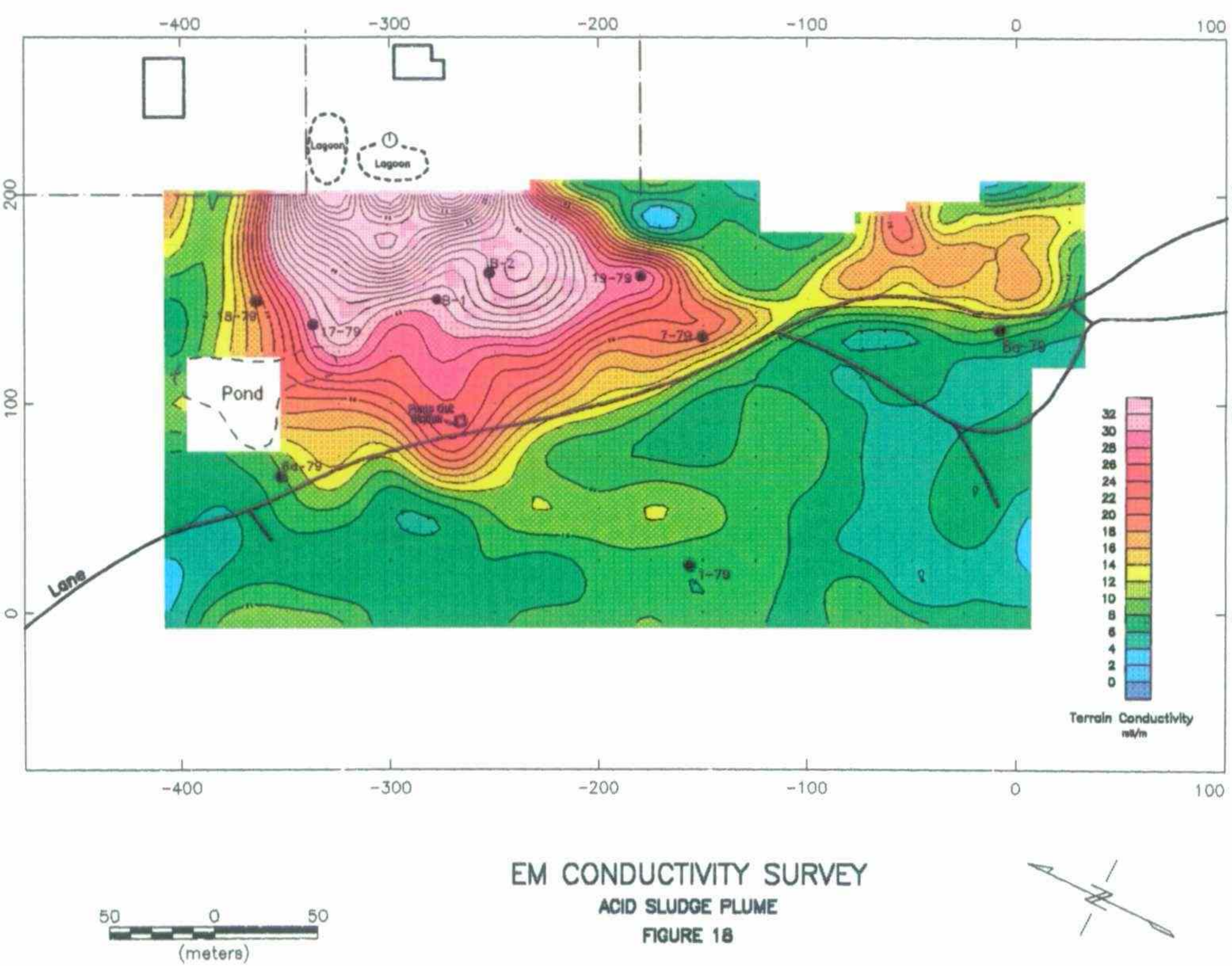
In the following four cases, only the Quad-Phase data was recorded in the vertical dipole mode.

4.21 THE DELINEATION OF AN ACID SLUDGE PLUME NEAR BRESLAU

Between 1960 and 1975, acid sludge was deposited in unlined lagoons at a plant in Breslau which produced the acid sludge as a byproduct of an oil reclamation process. Test wells down-gradient from the lagoons revealed groundwater contamination in the upper sand aquifer. To determine the direction and measurable extent of the contamination plume, an EM Conductivity Survey was conducted in November, 1984.

The geology consisted of a shallow and deep sand and gravel formation separated by a silty clay till. The shallow sand formation appears to thin towards the south, some of which may be due to past sand and gravel extraction. Leachate springs were evident at the time of the survey south-east of Test Well 7-79 (Figure 18).

The EM-31 survey was conducted on a general 25 metre grid over the area. In some areas, (where more rapid changes in conductivity were occurring) readings were reduced to a 12.5 metre spacing along the grid lines. Due to geographical changes which directly related to variations in the unsaturated thickness as well as changes in geology, the background values varied substantially between 1.2 and 12 mS/m. In Figure 18, the contamination plume in the shallow sand and gravel formation is outlined by the 14 mS/m contour.



EM CONDUCTIVITY SURVEY

ACID SLUDGE PLUME

FIGURE 18

KF, MOE, 1998

The shallow plume moves in a south-easterly direction which is approximately 90 degrees different than the groundwater flow direction in the lower sand and gravel aquifer which flows south-westerly towards the Grand River.[25,29]

4.22 THE MAPPING OF A LEACHATE PLUME FROM THE THESSALON LANDFILL SITE

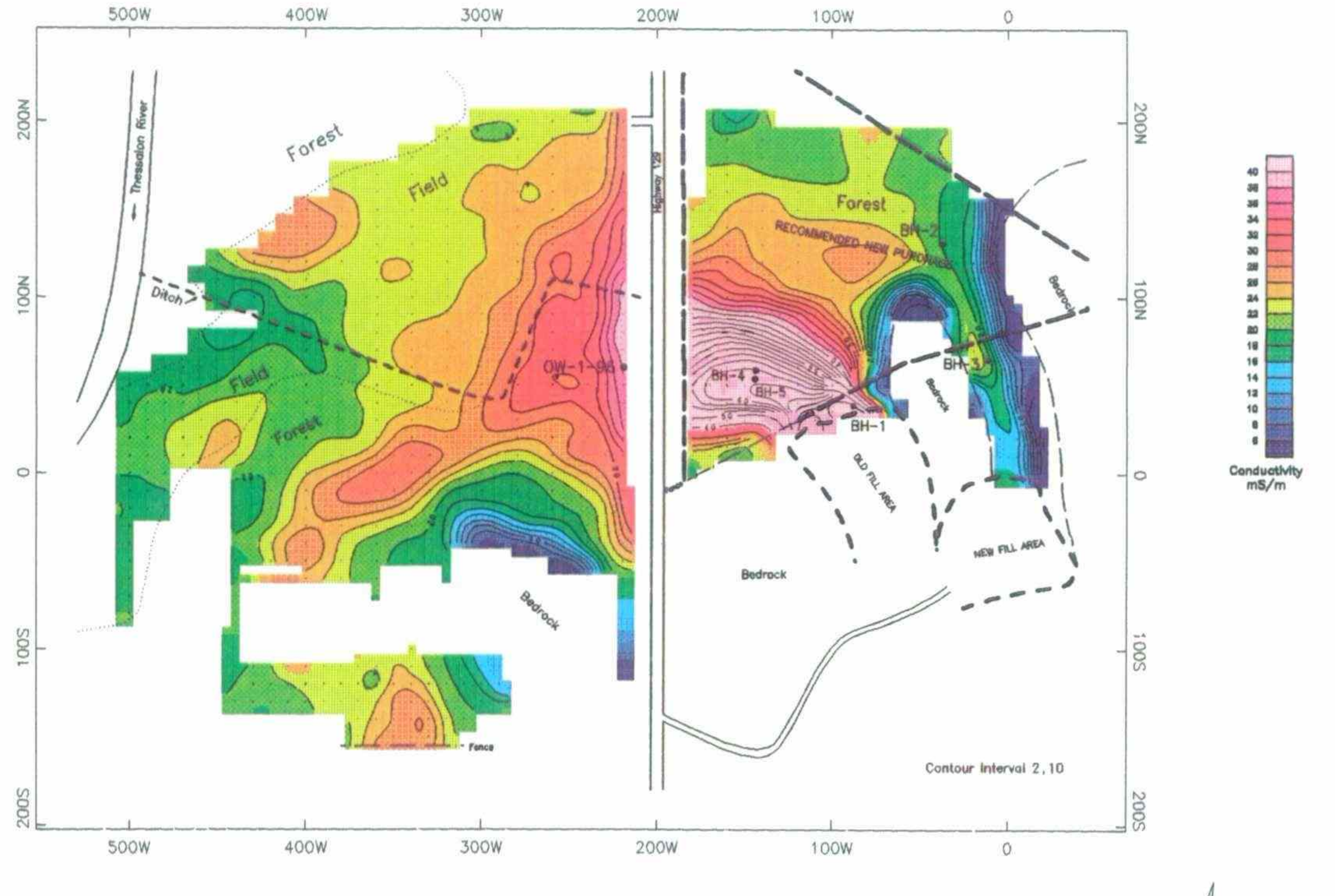
The Thessalon Landfill Site is located just north of the Town Of Thessalon on Highway 129. This site has been in operation as a disposal site from the mid 1930s. In 1971, a certificate of approval was obtained for the site which has been operating as a licensed landfill since that time. The site contains two fill areas. The old fill area was closed in 1995 when the new fill area was opened. The whole site is scheduled to be closed sometime in 1997, about six months after a new site for the area opens.

The geology in the area of the landfill site consists of a large bedrock ridge overlooking a relatively flat-lying glaciolacustrine silt and clay deposit to the north and west. The landfill site is located on the northerly edge of the bedrock ridge where two bedrock depressions were used as fill areas. The toe of the most westerly fill area, which has been closed for some time, is at the northern edge of the landfill property. The chloride concentrations for Boreholes 1 and 4, located down-gradient from the old fill area were 1130 mg/L and 1250 mg/L respectively indicating the site was out of compliance with the Ministry's Guideline B-7(Reasonable Use Policy).

GEOPHYSICS

In preparation for closure of the site, an EM Conductivity Survey was requested to map the direction and measurable extent of the leachate plume. This information would then be used to determine if wells down-gradient of the site are likely to be impacted and also to help determine the amount of land that would be necessary to be purchased in order to comply with the Ministry's Guideline B-7.

The survey was carried out on a base grid spacing of 10 by 20 metres which was reduced to a 10 by 10 grid in some of the plume areas. The terrain conductivity values recorded varied from a high of 74 mS/m at the toe of the old fill area to a low of 3 mS/m on the bedrock outcrop. In the area down- gradient of the new fill area, the terrain conductivity values were only 14 to 16 mS/m probably reflecting partial penetration of the induced electromagnetic field into the bedrock. Since the new fill area had only been in operation for a short time, the leachate plume from that area would also not be expected to be well developed. In areas where the overburden thickness was greater than 6 metres the background terrain conductivity values were approximately 24 mS/m. This value may also vary slightly depending on the degree of saturation of the area where the readings were recorded. The 30 mS/m terrain conductivity contour, shown in Figure 19, outlines the main contamination plume originating at the toe of the old fill area migrating westerly across Highway 129. The plume appears to continue along a slight depression in a southerly direction around



EM CONDUCTIVITY SURVEY

LEACHATE PLUME FROM THESSALON LANDFILL SITE

FIGURE 19

KF, MOE, 1998

a bedrock controlled hill. The actual extent of the plume in the slight depression would have to be determined by groundwater sampling.

In order to relate the groundwater chemistry with the EM conductivity plume across Highway 129, the Ministry requested that an additional well (OW-1-96) be installed at about the 38 mS/m contour west of Highway 129. The October 96 chemical analysis showed the chloride levels to drop from 1250 to 458 mg/L between BH-4 and OW-1-96 respectively. The consultant had previously calculated that using chlorides as the critical contaminant, the maximum level of chlorides at the point where the MOE Guideline B-7 (Reasonable Use Policy) would be met would be 128 mg/L. Using some simple calculations comparing the chloride levels and EM response at wells BH-4 and MW-1-96, the Ministry determined that the "Reasonable Use Policy" would be met at approximately the 29 mS/m contour on Figure 19.

CONCLUSIONS

1. The direction and extent of the contaminant plume would indicate that the private well, just north of the survey area should not be impacted.

2. Based on the geophysical survey and hydrogeology, the consultant recommended the purchase of a triangular shaped property north of the landfill site that would meet the Reasonable Use Guideline B-7.

3. The property west of Highway 129 is owned by the Town of Thessalon where the remainder of the contamination plume is contained. At the present time the plume is not reaching the river and the only other concern is that the town must take measures to ensure that drinking water wells are not constructed on the property in the future.

4.23 THE MAPPING OF A SALT CONTAMINATION PLUME FROM A STORAGE FACILITY IN MULMUR TOWNSHIP

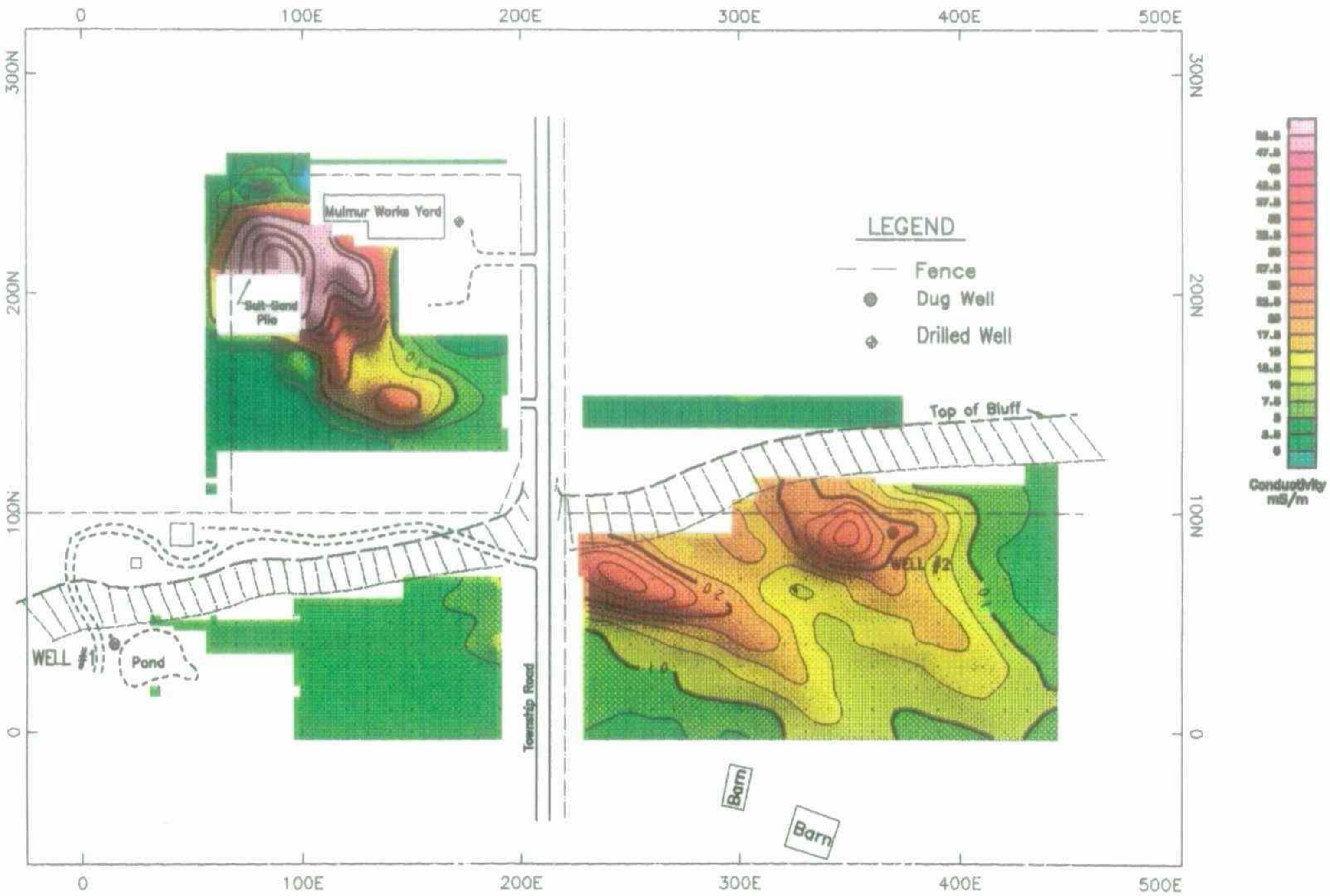
BACKGROUND

A salt contamination complaint from a property owner near the Township of Mulmur Works Yard, resulted in an EM Conductivity Survey to determine the direction and measurable extent of the contamination plume originating from the works yard. The Township had maintained an uncovered salt-sand pile for winter road salting operation for 13 years prior to the EM Conductivity Survey in 1987. Three wells in the area of the Works Yard included the Townships drilled well and two privately owned dug wells referred to as dug wells number 1 and 2 in Figure 20. The township well was drilled through mainly sand and gravel to shale bedrock at 29.5 metres. Dug well #1 (2 tiles deep) was located approximately 150 metres south-west of the salt-sand pile and dug well #2 (2.5 tiles deep) was located approximately 300 metres south east of the salt-sand pile. On December 8, 1986, chloride concentrations for the township well and dug wells #1 and 2 were 1.0, 3.0 and 983 mg/L respectively. The Township was reluctant to assume responsibility for the salt contamination in dug well #2 since dug well #1 was closer to the salt-sand pile and was not contaminated.

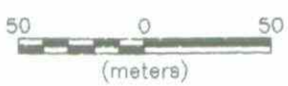
The geology of the area surveyed was described by Chapman and Putnam as being part of a glacial spillway. The township well indicates mainly sand and gravel to the top of a shale bedrock at 29.5 metres. The elevation of the township salt-sand pile was approximately 10 metres higher than both dug wells #1 and #2 which are located at the base of a bluff where the groundwater table was shallow.

GEOPHYSICS

The EM Conductivity Survey was carried out with the Geonics EM-31 Terrain Conductivity Metre. The Quad-Phase data was recorded on a 10 metre grid with the instrument in the vertical dipole mode. Figure 20 indicates a contamination plume to originate at the salt-sand pile and migrate in a southeasterly direction. Due to the deep water-table in the vicinity of the salt-sand pile, the chloride plume disappears below the depth penetration of the instrument (6 metres) within 100 metres of the source. Below the bluff, the water table was shallow and the plume reappears in what appears as two point sources and continues to migrate in the same direction to the southeast. The plume is still detectable 400 metres from the source. The privately owned well #2 was located just inside the 20 mS/m contour. The background values for the area below the bluff ranged between 6 and 8 mS/m.



EM CONDUCTIVITY SURVEY
SALT CONTAMINATION PLUME
FIGURE 20



KF, MOEE, 1997

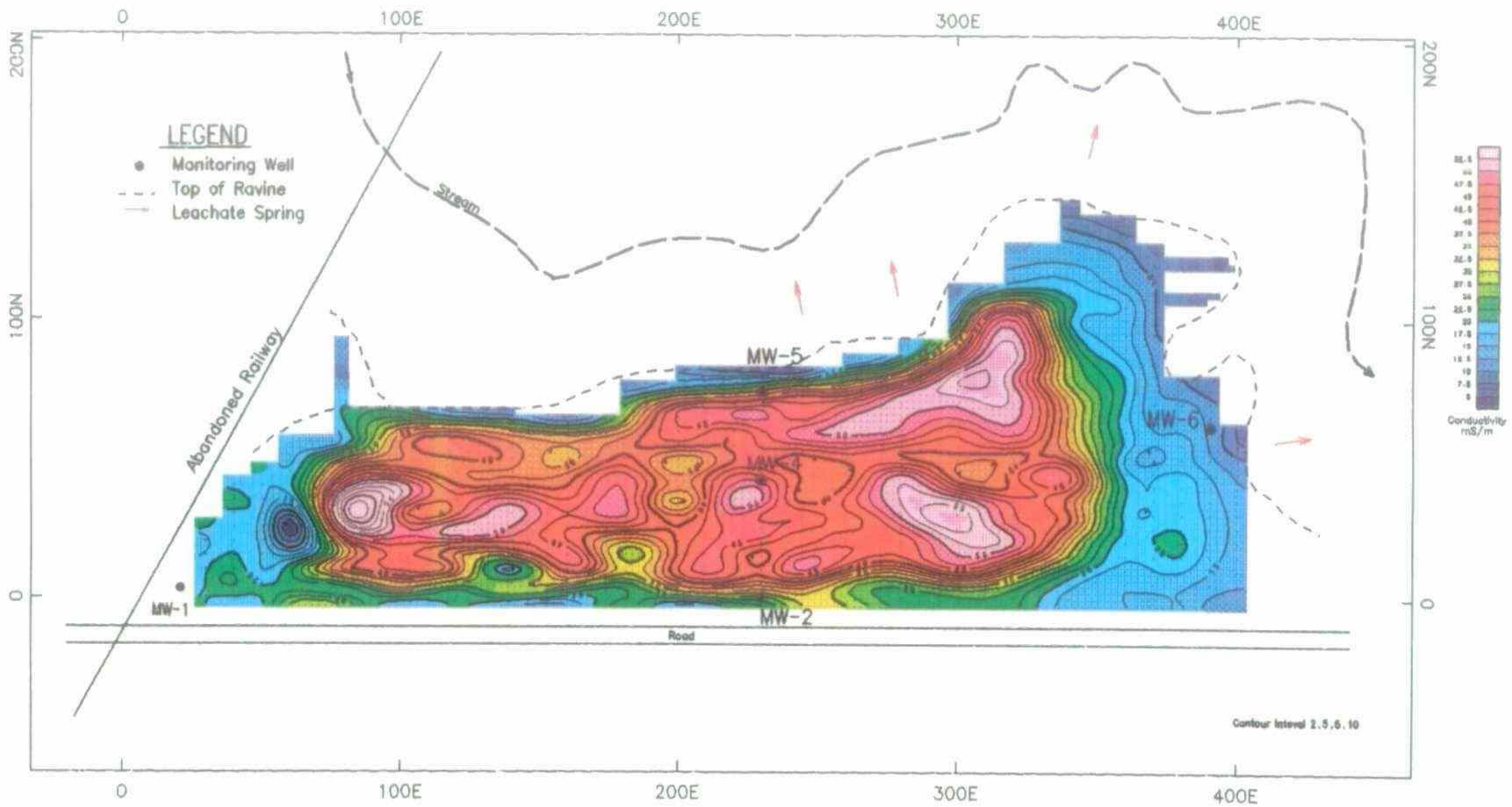
CONCLUSIONS

The contamination plume clearly identifies the groundwater flow direction to be towards the southeast in the direction of the Pine River. Privately owned well #2 was definitely located within the plume from the salt-sand pile and as a result of this survey, the Township assumed responsibility for replacing the water supply for that property. Privately owned well #1 was not affected since it was outside the contamination plume, and due to the groundwater flow direction, will not be affected in the future.

4.24 EM CONDUCTIVITY SURVEY TO DETERMINE THE AREA OF A CLOSED LANDFILL SITE AFTER IT HAD BEEN RETURNED TO AGRICULTURAL USE

In many cases the location of former waste sites are difficult to find especially if there is no visible mounding. The surface may be reforested, returned to agricultural use or used for some other purpose. One of the ways to relocate these sites is by carrying out an EM Conductivity Survey. The following example is at a closed waste site near Tillsonburg.

Figure 21. Photograph showing western section of former landfill after it was returned to agricultural use. Monitoring Well 5 in foreground.



EM CONDUCTIVITY SURVEY

LOCATION OF CLOSED LANDFILL SITE

FIGURE 22

25 0 25 50 75

(meters)

KF, MOEE, 1997

BACKGROUND

Before this site became a waste disposal site, it was described as an excavated burrow pit[26] of clay and sandy soil. The depth of the pit was about 14 metres and was about 2.8 hectares in size. In 1971 a certificate of approval for a landfill site was obtained for the handling of 90% domestic and 10% commercial, industrial and construction debris. The site was operated until 1979 when it was covered with sufficient top soil to be returned to agricultural use. At the time of the survey in 1992, it was being used to grow corn. The photograph shown in Figure 21 shows a section of the site taken from just east of OW-5 looking south-west.

GEOLOGY AND TOPOGRAPHY

The geological log for MW-1[26] which is considered to represent the natural conditions at the site was as follows:

0 - 13.3m	clean fine sand
13.3 - 15.2m	silty fine sand
15.2 - 15.5m	silty clay

The monitoring wells drilled through the garbage indicated that the final cover material for the site consisted of silty clay varying between 0.9 and 4.3 metres thick. The topography of the site is generally flat with a ravine bordering the northern and eastern edge of the site. The elevation difference between the top of the site and the stream (Tributary of Big Otter Creek) is about 15 metres.

GEOPHYSICS

The EM Conductivity Survey was carried out by recording terrain conductivity values every 5 metres along grid lines spaced 20 metres apart. Background terrain conductivity values for the area surrounding the landfill site are in the range of 10 to 15 mS/m. On the landfill site, the terrain conductivity values ranged between 20 and 55 mS/m. The edge of the landfill site would appear to be outlined somewhere between the 25 and 30 mS/m contour.

CONCLUSIONS

With reference to Figure 22, the landfill site appears to be contained within the 25 to 30 mS/m terrain conductivity contour. Although the EM conductivity method is not the only geophysical method applicable for locating buried wastes, it is fast and effective when mapping such large areas.

4.3 VLF RESISTIVITY

The VLF Resistivity Survey is another option in mapping contaminant plumes. Under certain conditions where a highly resistive and uniform formation overlies or contains a deep channelized conductive layer, such as a contamination plume, this method works well. However, due to the variable depth of penetration which is dependent on the formation resistivity, care in data interpretation has to be exercised. The two applications of VLF Resistivity Surveys which follow are a salt contamination plume from a salt storage facility and a leachate plume generated by a landfill and sewage lagoons.

4.31 A VLF RESISTIVITY SURVEY OF A SALT CONTAMINATION PLUME FROM A STORAGE FACILITY IN ORONO

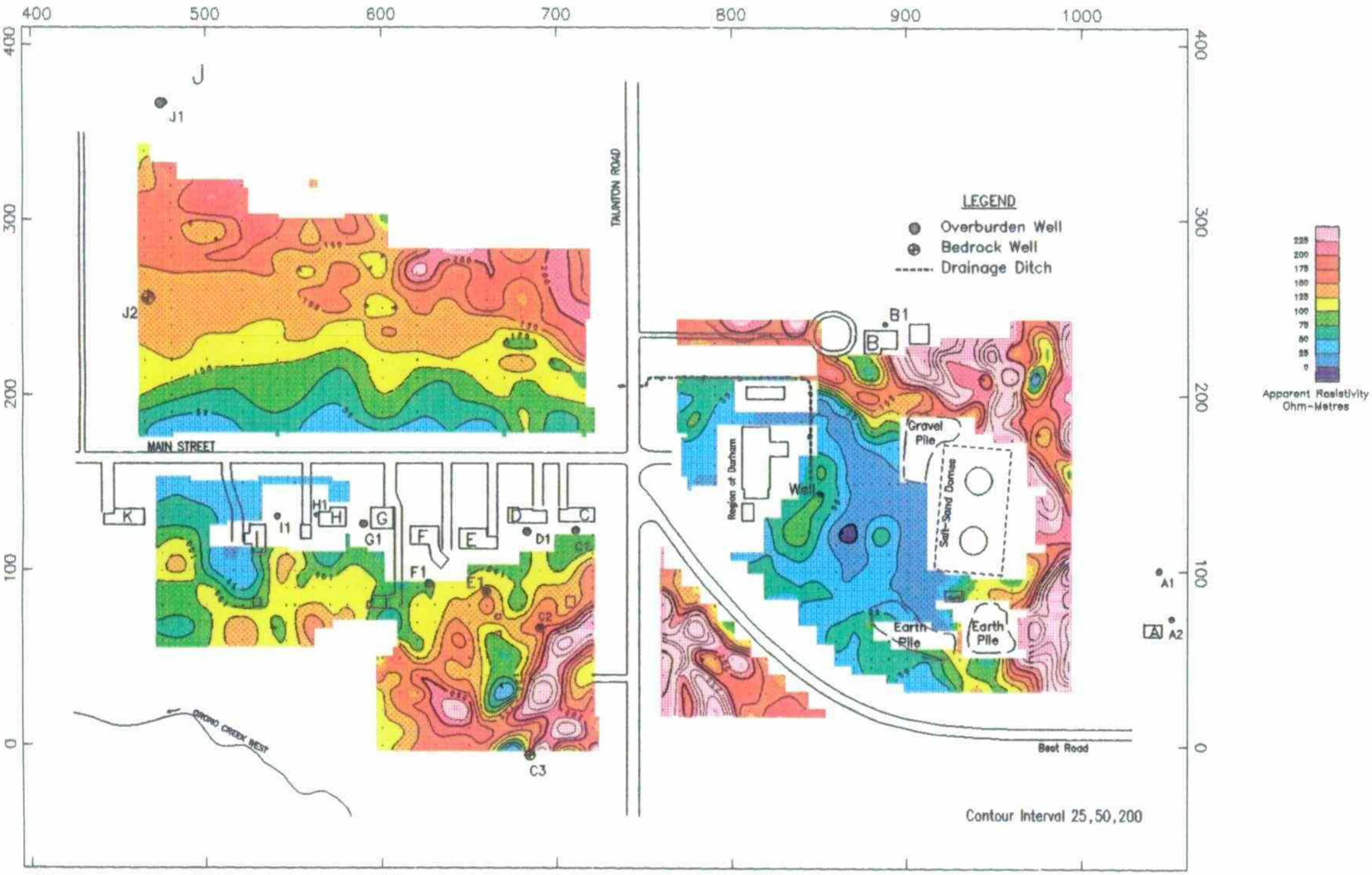
The patrol yard operated by the Region of Durham has stored salt on the property for use in winter road de-icing for several years. Since about 1979 the salt has been stored in domes to minimize groundwater contamination. Several wells south of the storage facility developed salt contamination problems and as a result of this contamination, a geophysical survey was requested to try and identify the probable source. The sources considered were from road salting operations, the salt storage facility and water softeners.

GEOLOGY

South of the Taunton Road (Figure 23), the drillers' logs generally indicate sand over a sandy clay. The sand appears to thicken on properties E, F, and G where only sand is encountered to depths of 25.5, 24.4, and 12.2 metres respectively. North of the Taunton Road, the wells at Durham Region and property A show clay till to a depth of 41 and 17 metres respectively. The surface geology in the triangular property between Best Road and the Taunton Road is similar to a fine beach sand.

VLF RESISTIVITY SURVEY

The VLF Resistivity Survey was carried out using the Geonics EM16R VLF Resistivity Metre. Both the apparent resistivity and the phase angles were recorded on a 10 by 10 metre grid except in the open field south of Taunton Road and west of Main Street where the grid was increased to 10 by 20 metres. The VLF radio transmitter used for this survey was NSS in Maryland with a frequency of 21.4 KHZ.



VLF RESISTIVITY SURVEY IN ORONO

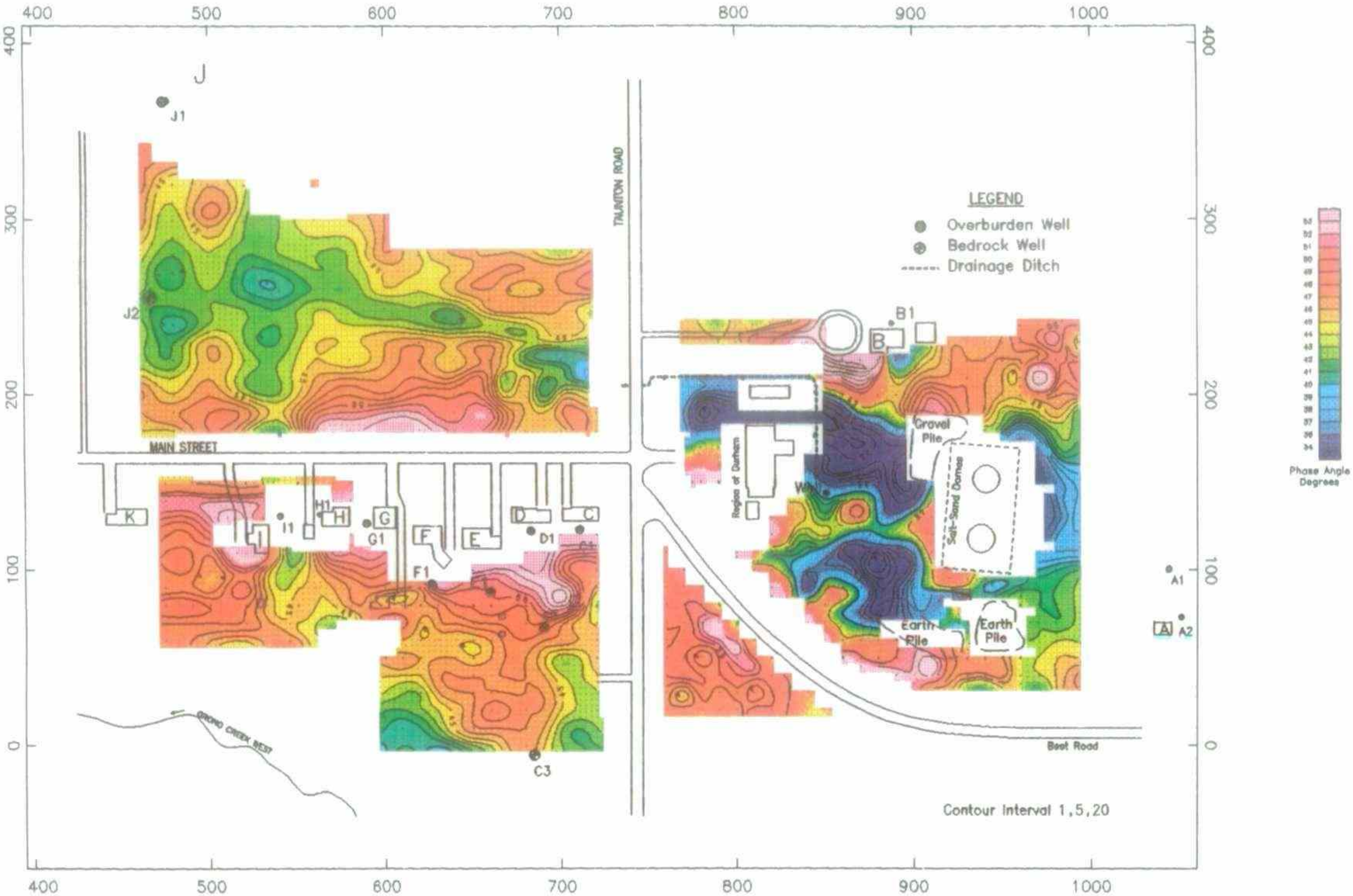
APPARENT RESISTIVITY MAP OF SALT CONTAMINATION PLUME

FIGURE 23

50 0 50 100

(meters)

KF, MOE, 1998



VLF RESISTIVITY SURVEY IN ORONO

PHASE ANGLE MAP OF SALT CONTAMINATION PLUME

FIGURE 24

KF, MOE, 1998

APPARENT RESISTIVITY

In Figure 23, apparent resistivity values greater than 150 ohm-metres are assumed to be background. These values were recorded on the north and west sides of the Region of Durham Works Yard as well as in the triangular area between Best Road and the Taunton Road. Background values were also recorded on the east sides of properties C, D and E and along the west side of the open field surveyed west of Main Street (property J). No values were recorded on the front lawns of properties C,D,E,F and G due to interference from buried cables. The lowest apparent resistivity values, around 10 ohm-metres were recorded south of the salt domes where some salt contamination would occur through yard operation. The areas of lowest apparent resistivity are outlined by the 50 ohm-metre contour. These areas are located in the Region of Durham Works Yard and south of the Taunton Road centred along Main Street.

PHASE ANGLES

The phase angles indicate a geological model of two or more layers where the formations are either increasing or decreasing in resistivity with depth. Where contamination occurs, the contaminated layer acts as a different geological layer because of its different resistivity value.

On the patrol yard property (Figure 24), the 40 degree contour outlines areas of near surface contamination probably due to various yard activities as well as surface drainage. South of the Taunton Road, the phase angles outline two areas of interest. The first area is in the vicinity of the contaminated wells along Main Street where the phase angles are greater than 50 degrees indicating decreasing resistivity with depth. This fits with the known geology of resistive dry surface sand decreasing in resistivity with depth due to the contaminated groundwater. The second area of interest is the elongated green area on property J west of Main Street which extends south from the Taunton Road to the south edge of the survey. The green area outlines a slight depression in the field indicating that the surface soils are more conductive than the lower geology. This may be partly due to the ditch from the patrol yard crossing the Taunton Road and discharging salty water into this depression during spring run off. Any resulting surface contamination in this depression does not appear to have an effect on the over-all resistivity (see Figure 23) and does not change the appearance of the main contamination plume.

CONCLUSIONS

In Figure 23 the 150 ohm-metre resistivity contour was chosen arbitrarily as approximately representing the edge of the contaminant plume. The actual plume, however, will extend further than can be mapped with geophysics. Using the 150 ohm-metre contour, the contaminant plume originating at the salt-sand domes, moves easterly towards Best Road and southernly centring approximately on Main Street. The plume actually appears to extend south along Main Street past the area surveyed. Chemical analysis of wells sampled along Main Street on April 28, 1995 indicated that for the chloride parameter, only the wells on properties H and I were over the aesthetic objective of 250 mg/L for drinking water. The other wells sampled along Main Street to the north showed elevated chloride levels but were under the aesthetic objective. Since these wells are closer to the main source of contamination, it might be expected that the chloride levels would be higher. There are, however, several reasons why the level of contamination shown in various wells along the plume may vary:

(1) The salt concentrations entering the groundwater flow system may vary with time due to seasonal yard usage and precipitation variances.

(2) The depth of well intakes or sampling depth within the well with respect to the plume thickness could have a significant effect on the chloride level obtained during sampling since the chloride will concentrate near the bottom of the aquifer.

(3) With the construction of the salt domes the concentration of chlorides entering the aquifer should have decreased with time. A concentrated slug of chloride contaminated water may be moving along the flow path and may have just reached the properties H and I at this time. This is the conclusion expressed in the MOEE Report[7] entitled Ground Water Investigation of Salt Contamination on North Main Street, Orono. Also in the report, calculations based on the present data and well samples taken in 1987 where the highest chloride levels were in the wells on properties E and F, a possible slug of high chloride water may be moving at a rate of 26 metres per year.

The other two possible sources of salt contamination in the area were from road salting operations and water softeners. The actual effect of road salting along Main Street is impossible to determine since it centres on the larger plume from the Region of Durham yard. The effect should be similar to that of the Taunton Road where no significant plume appears in the surveyed area. Water softeners will have some local effect. The only septic bed which stands out is on property I. This septic bed coincides with the blue area south east of the house and should not affect either of the wells on properties H and I since it is down gradient from the wells.

It was concluded that the major source of salt contamination in the wells along Main Street is from the Region of Durham Yard. By comparing Figures 23 and 24 in the vicinity of the contaminated wells along Main Street, the area contained by the 50 ohm-metre apparent resistivity contour in Figure 23 is very similar to the area outlined by the 50 degree phase angle in Figure 24. This similarity in area of low resistivity values and high phase angle further supports the theory of the presence of a buried sand filled channel. Such a buried channel would provide a conduit for high chloride water in the vicinity of the Region of Durham's Yard to move down-gradient towards the wells along Main Street.

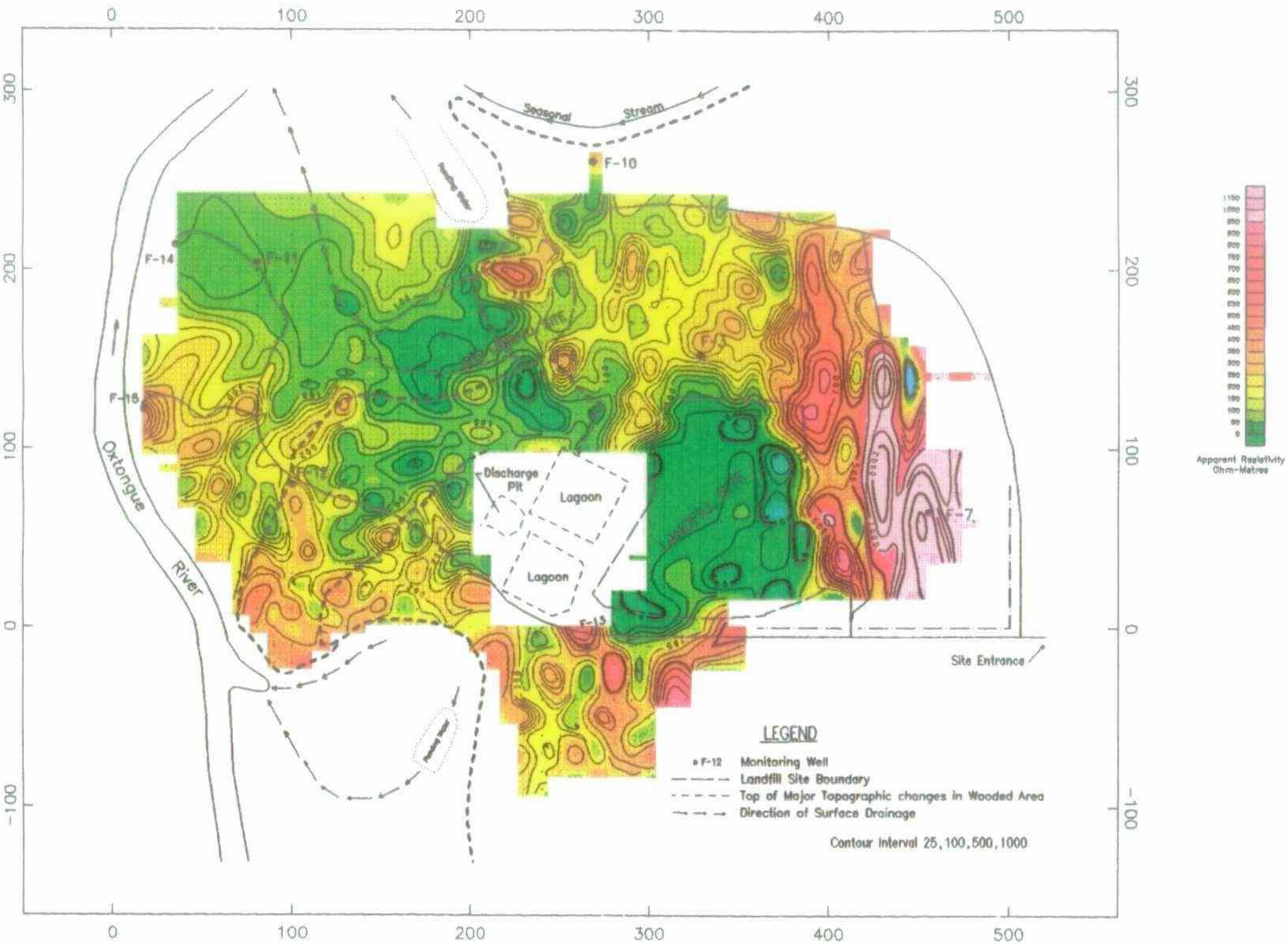
4.32 THE MAPPING OF LEACHATE PLUMES FROM THE LANDFILL AND SEWAGE LAGOONS AT THE FRANKLIN SITE WITHIN THE LAKE OF BAYS TOWNSHIP

The Franklin Landfill Site is located about 3 kilometres east of Dwight in the Township of Lake of Bays. The site is in a former gravel pit in an upland area approximately 300 metres north of the Oxtongue River. In addition to the present fill area there is an old fill area which has been closed for several years and two sewage lagoons which the municipality operates.

Several monitoring wells were installed on the site between 1989 and 1995 as part of a hydrogeological investigation. In 1995, an additional two monitoring wells were requested to further define the leachate plumes from both the landfill areas and the sewage lagoon to determine if there is potential for surface water impact. The geophysical survey was requested to help site these wells by determining if there were separate plumes form the landfill areas and sewage lagoons and to map measurable extent and direction of such plumes.

GEOLOGY AND TOPOGRAPHY

The observation wells indicated that the overburden consists of mainly fine to medium sand over the precambrian bedrock. The overburden thickness is 18 metres at monitoring well F-7 and decreases in thickness towards the Oxtongue River where it outcrops on the south bank. South of the present landfill area, the surface topography drops abruptly in two terrace like steps of between 3 and 5 metres each.

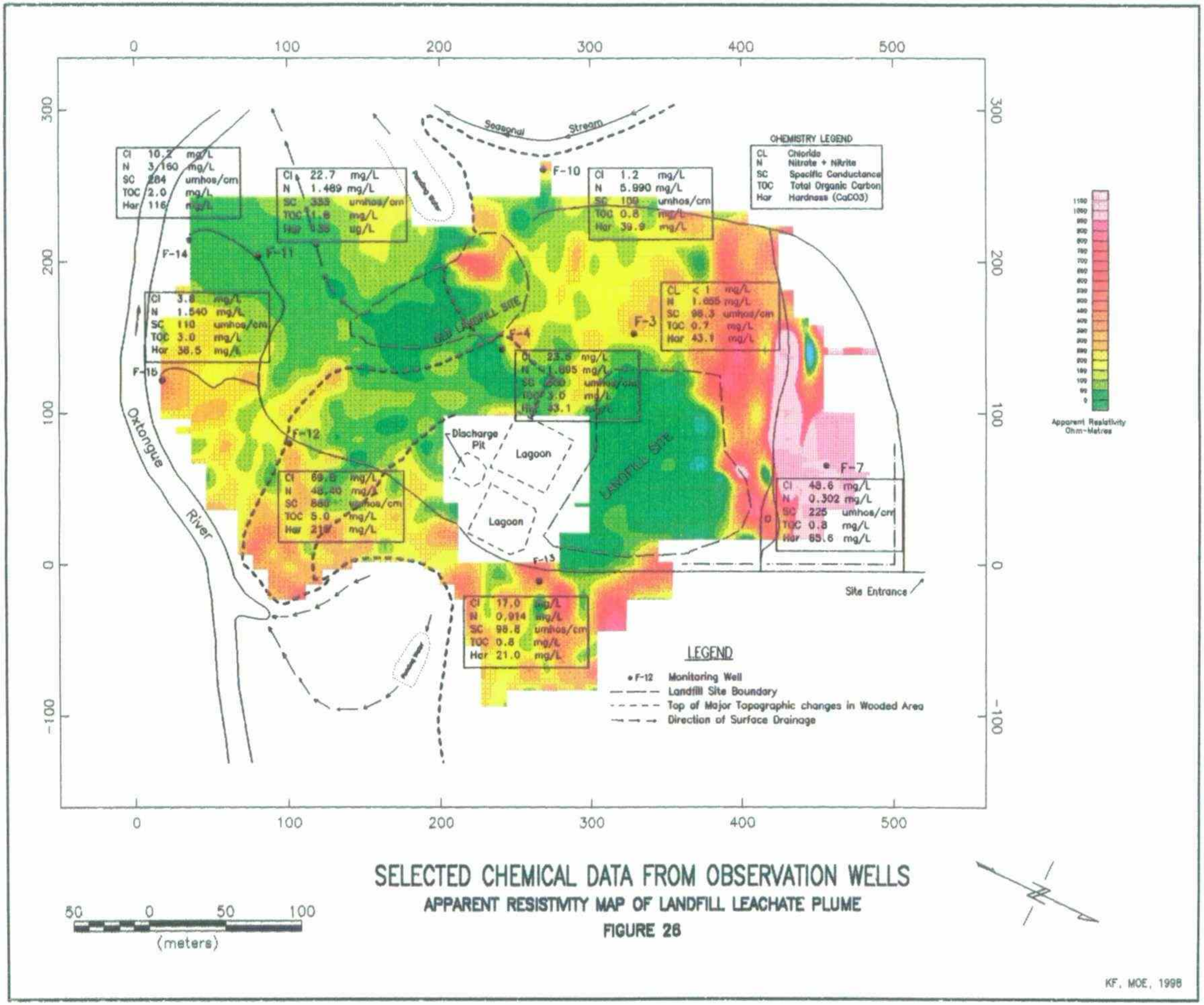


VLF RESISTIVITY SURVEY

APPARENT RESISTIVITY MAP OF LANDFILL LEACHATE PLUME

FIGURE 25

KF, MOE, 1998



SELECTED CHEMICAL DATA FROM OBSERVATION WELLS

APPARENT RESISTIVITY MAP OF LANDFILL LEACHATE PLUME

FIGURE 26

In the landfill site area, there are three drainage channels which probably receive groundwater discharge for at least part of the year (when the groundwater table is high). These areas are as follows:

1. The seasonal stream on the north and west sides of the landfill.

2. On the neighbouring property south-east of the lagoons, surface water was found ponding in September, 1995. This pond is probably spring fed.

3. The old landfill site was placed at least partly in a depression. Water was found ponding in September 1995 off the north-west corner of the old site and drained away in a south-westerly direction. At the south end of the old landfill the surface drainage followed a depression in a southerly and then in a south-westerly direction. Both of these surface drainage channels reach the Oxtongue River just east of the mouth of the seasonal stream.

VLF RESISTIVITY SURVEY

The VLF Resistivity was chosen for this survey because of the high surface resistivity, the depth to water table in some areas and the necessity to work in a mature forest without cut lines for about half the area surveyed. Both apparent resistivity values and phase angles were recorded on a 10 by 20 metre over most of the area with a reduced grid of 10 by 10 metres in some areas. The VLF radio transmitter used for this survey was NSS in Maryland with a frequency of 21.4 KHZ.

North of the present landfill, the apparent resistivity values were greater than 300 ohm-metres and in some areas reached values greater than 2000 ohm-metres (Figure 25). Areas where the apparent resistivity values were greater than 2000 ohm-metres were most likely due to the effect of the bedrock which appeared to be more shallow at the north side of the property. Bedrock outcrops along Highway 60 about 400 metres north-east of the landfill property. The apparent resistivity value measured on the above bedrock outcrop was 5000 ohm-metres. At the north end of the landfill site, the depth to bedrock was recorded as 18.3 metres in monitoring well F-7.

The apparent resistivity values recorded on the present and old landfill sites ranged between 20 and 50 ohm-metres with the exception of near the north end of the old landfill where the apparent resistivity values were higher. A small area of greater than 400 ohm-metres was probably due to some resistive material disposed there. The contaminant plume from both landfill sites and the lagoon discharge pit are outlined by the 100 ohm-metre contour. The main contaminant plume starts at the south end of the present landfill and moves in a southerly direction passing through the southern section of the old landfill site and continuing past monitoring wells F-11 and F-14 where the plume enters the Oxtongue River. It should be noted that the plume does not follow the surface depression shown by the arrows from the toe of the old landfill site but continues southward towards the river.

Just south of the lagoon disposal pit, the plume fans out into a secondary plume which moves south-easterly towards monitoring well F-12. This secondary plume is less distinct past monitoring well F-12 but probably continues in the same direction following the slightly lower resistivity areas and entering the river east of monitoring well F-15. The narrow zone of high resistivity values along the top of the change in topography at F-12 is probably due to changes in soil moisture near the edge of the 5 metre change in elevation.

In Figure 26, the June 1995 chemistry data from water samples taken by Proctor and Redfern Ltd. are shown. Monitoring wells F-4, F-11 and F-14 are located in the main plume and monitoring well F-12 is in the secondary plume to the east. Monitoring well F-12 shows the highest nitrate values probably due to the discharge from the sewage lagoons. The chloride levels in monitoring well F-7 seems anomalous. Since the well is located up-gradient from the landfill site, the landfill can-not be the source of the chloride. One explanation for the chloride level could be the result of winter road salting operations along the entrance road to the landfill. The reason why the geophysics isn't indicating a lower resistivity value in this area is that the conductivity value measured in F-7 is only around 225 umhos/cm and the saturated thickness is relatively thin sandwiched between two resistive formations, well sorted sand and gravel and the precambrian bedrock.

CONCLUSIONS

1. The main contamination plume outlined by the 100 ohm/metre apparent resistivity contour starts at the base of the present landfill and moves in a southerly direction through the lower section of the old landfill site continuing past monitoring wells F-11 and F-14 to the Oxtongue River.

2. A secondary plume also outlined by the 100 ohm/metre apparent resistivity contour breaks away from the main plume just south of the lagoon's discharge pit and moves south easterly towards monitoring well F-12. The high nitrate levels in monitoring well F-12 would also suggest that the discharge pit from the lagoons is contributing to the plume at that location. Although not as well defined with the geophysics, the secondary plume probably continues along the same direction following the slightly lower resistivity areas and entering the river east of monitoring well F-15.

3. Two other areas where off site impacts may occur are in the area of the two surface ponds on each side of the landfill. These are probably minor in comparison to the main plumes.

RECOMMENDATIONS

The monitoring wells F-11, F-12 and F-14 are presently monitoring the main plumes, however, an additional monitoring well in the vicinity of co-ordinates 40N 80W would measure any impact to the river down gradient of monitoring well F-12. In addition, a ground water sample in the vicinity of the east surface pond should be taken to determine if there is any significant impact off site in that direction.

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